PROJECT LEVEL HIGHWAY MANAGEMENT FRAMEWORK

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ABSTRACT

Saskatchewan Highways and Transportation (SHT) is responsible for 26,125 km of highways in the province. The highway system is divided into primary and secondary highways. The primary highway system provides an inter-regional, inter-provincial, and inter-national highway network that was built to accommodate traffic volumes in excess of 4,000 vehicles per day with significant numbers of heavily loaded trucks. The secondary highway system consists of structural, thin membrane surface (TMS), and gravel highways. TMS highways were constructed to provide feeder links into the primary system for relatively low volumes of traffic with few heavily loaded trucks.

Years of increasing volumes of heavy trucks and inadequate funding on the TMS highway system have forced SHT to evaluate various management strategies. New maintenance and management strategies like partnerships with Rural Municipalities and full depth in-place chemical strengthening have been developed and, along with conventional management strategies, are being used throughout Saskatchewan.

The purpose of this research is to develop a project level analytical framework capable of evaluating management strategies for secondary highways, based on SHT surfacing and structure standards. The best management strategy is the lowest total cost strategy (agency and road user) based on SHT standards. Probabilistic modeling was also included in the framework so uncertainty in the variables, like length of the service

life of these new strategies, could be analyzed. A project on Highway No. 19 was evaluated to demonstrate the framework. From the analysis, the full depth in-place chemical strengthening was the preferred strategy if it lasted 15 to 20 years, relative to a 15 year expected life of the conventional strategy. As well, as the technology advances in Saskatchewan, it appears that the full depth in-place chemical strengthening should decrease in cost while the conventional strategy increases in cost as aggregate sources are depleted. This trend should result in long-term cost savings to SHT.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Saskatchewan Highways and Transportation (SHT) is responsible for 26,125 km of highways in the province of Saskatchewan. The highway network is divided into the primary and secondary highway systems, consisting of structural, thin membrane surface (TMS), and gravel highways, as shown in Figure 1.1.

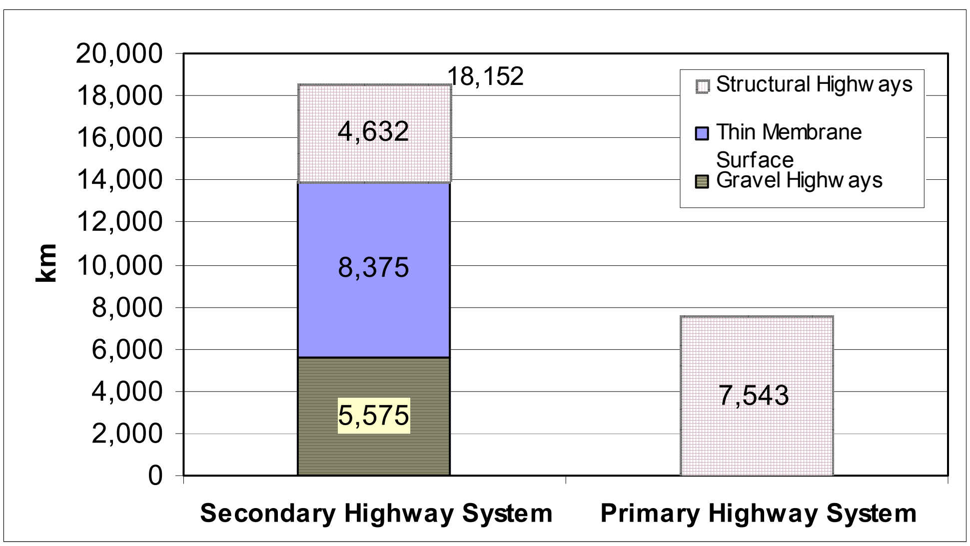


FIGURE 1.1 BREAKDOWN OF HIGHWAY SYSTEM IN SASKATCHEWAN

The primary highway system is in place to provide an interregional, interprovincial, and international highway network, including urban connectors. The Saskatchewan primary highway system has been built to accommodate traffic volumes over 1800 vehicles per day and significant numbers of heavily loaded trucks (SHT

2001a). The primary system supports 71% of the total Saskatchewan traffic (Blomme 2000). Traffic volumes typically range from 2,000 to 6,000 vehicles per day with 15% to 30% commercial vehicles. For example, Highway No. 16 carries 2,500 vehicles per day and 24% truck traffic by Lanigan and 4,000 vehicles per day and 23% truck traffic by Radisson (SHT 2002). To accommodate the heavily loaded trucks, the primary highway system is constructed of structural pavements. These pavements are built with granular strengthened roadbeds and an asphalt-concrete surface. A typical cross section is illustrated in Figure 1.2.

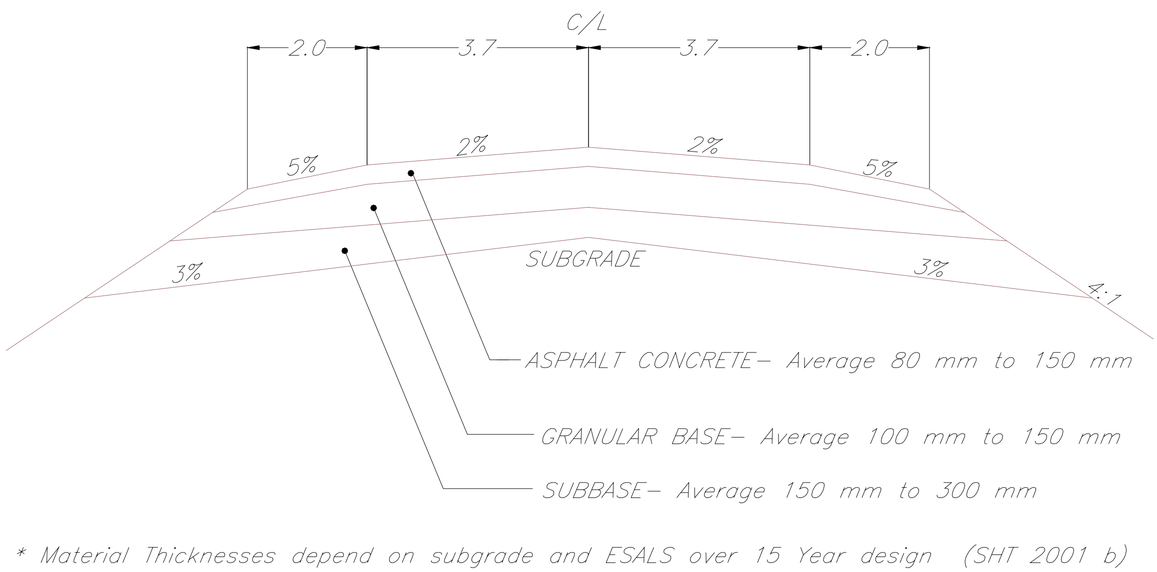


FIGURE 1.2 TYPICAL CROSS SECTION FOR PRIMARY HIGHWAY

Because the primary highway system carries high traffic volumes, it is designed to high geometric standards. Table 1.1 provides typical design values for the primary and secondary highway system. Surfaces on primary highways are typically designed with a 15 year service life, and are generally preserved up to 30 years with timely maintenance.

TABLE 1.1 PRIMARY VERSUS SECONDARY SYSTEM

	Units	Primary Highway System	Secondary Highway System	
Traffic Volume (AADT)	vehicles/day	>1800	700-1800	150-700
Divided (D)/ Undivided (UD)		D or UD	UD	UD
Constructed Surface		Asphalt Concrete (AC)	Double Seal (DS) or AC	DS
Rehabilitation		AC or DS	AC or DS	DS
Design Speed	km/hr	130	120	110
Sideslopes	hor/ver	4:1 to 10:1	4:1	4:1
Lane Width	m	3.7	3.7	3.0
Design Shoulder Width	m	3.0	1.5 to 2.0	1.0
Passing Sight Distance	m	1170	1025	900
Horizontal Alignment	Radius (min)	700 m min.	597 m min.	475 m min.
Right of Way	m	62 to 106 (Divided)	62	44

The secondary highway system is in place to provide access and important links between segments of the primary system and communities for the purpose of social interaction and to support economic activity. Secondary highways are built to lower geometric standards relative to the primary system, as shown in Table 1.1. The secondary highway system consists of structural, gravel, and TMS highways. A typical cross section for a secondary highway with traffic volumes between 150 vehicles per day and 700 vehicles per day is illustrated in Figure 1.3. The structural highways on the secondary system are lower traffic volume highways than the primary system and TMS highways that have been strengthened over the years. Most of the gravel highways are roads accessing the mining and forestry industries in northern Saskatchewan. The secondary highway system provides important links in the Province of Saskatchewan.

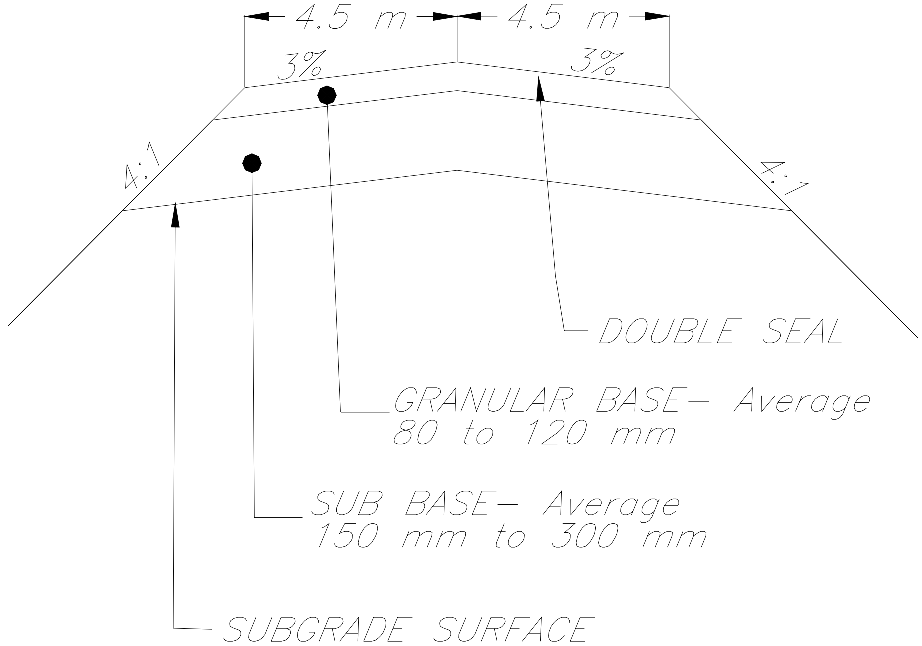


FIGURE 1.3 TYPICAL CROSS SECTION FOR SECONDARY HIGHWAY

Transportation plays an important role in the revitalization in rural Saskatchewan. Stabler and Offert (1996) describe the changes in Saskatchewan from 1961 to 1995 and the future outlook. The report states that the retention of hospitals, special health care facilities, and high schools in communities that are no longer commercially viable will neither enhance a community's prospects for rejuvenation nor prevent further decline. They define the concept of a community in such a way that it encompasses the entire area within which people live, work, shop for everyday goods and services, go to school from kindergarten to 12, obtain routine medical services, and find much of their recreation and entertainment.

Between 1961 and 2001, the pattern has been one of consolidation (Stabler et. al. 2002). The Communities within the complete and partial shopping centre classification have dropped from 128 communities in 1961 to 29 in 1995 (Stabler et. al. 2002). With the consolidation of communities, rural Saskatchewan will continue to decline in population, thus affecting the role of the secondary highway system. Saskatchewan needs the secondary highway system to be able to serve existing, and to foster new, economic activity, as this is a main function of highway infrastructure. Regulations and policies like secondary weight restrictions must not hinder the economic viability of industry. While communities and infrastructure in rural Saskatchewan are consolidating, changing, and even disappearing, there are opportunities emerging and SHT must be able to provide the infrastructure as transportation plays a vital role in the optimized decline of many of these new ventures.

TMS highways are non-structural roads that were built in the 1960s and 1970s to provide cost-effective dust, mud and stone free surfaces to local rural residents. Figure 1.4 illustrates the difference between a TMS and structural highway. The TMS network has operated effectively and efficiently for three to four decades, prior to the increased loading currently underway (Gerbrandt and Warrener 2001). TMS highways are low-volume highways that typically support under 500 vehicles per day (SHT 2002). The secondary system provides an important link in the province and is valuable to the scattered population.

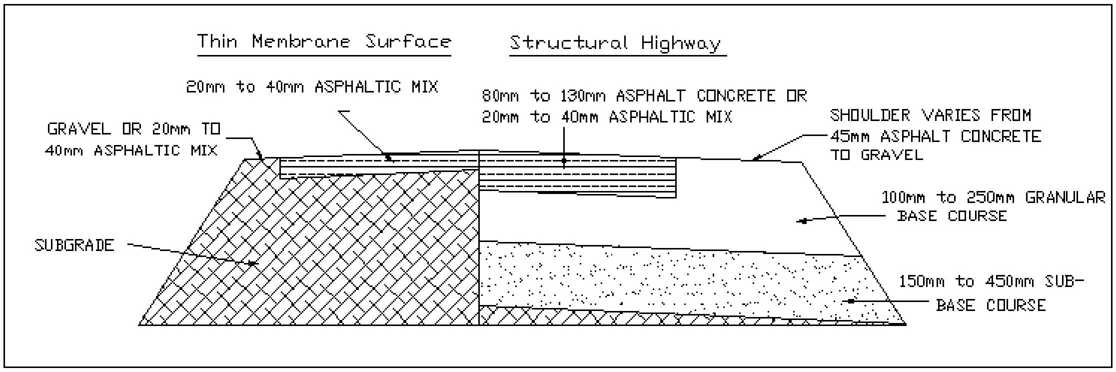


FIGURE 1.4 TMS VERSUS STRUCTURAL HIGHWAY

Some of the increasing pressures on the secondary road system are illustrated in Figure 1.5. The closure of grain elevators and rail line abandonment has resulted in an increase of trucks on the highways; trucks are now required to travel farther to get to inland terminals so that they have increased in size and carrying capacity to make hauling more economical. From 1985 to 1998, the number of elevators has decreased from 1,045 to 637 (Government of Saskatchewan 1998). Overall, grain haul by truck on a tonne-kilometre basis in the province of Saskatchewan is currently 17 times what it was in the early 1970's (Ray Barton Associates 1998).

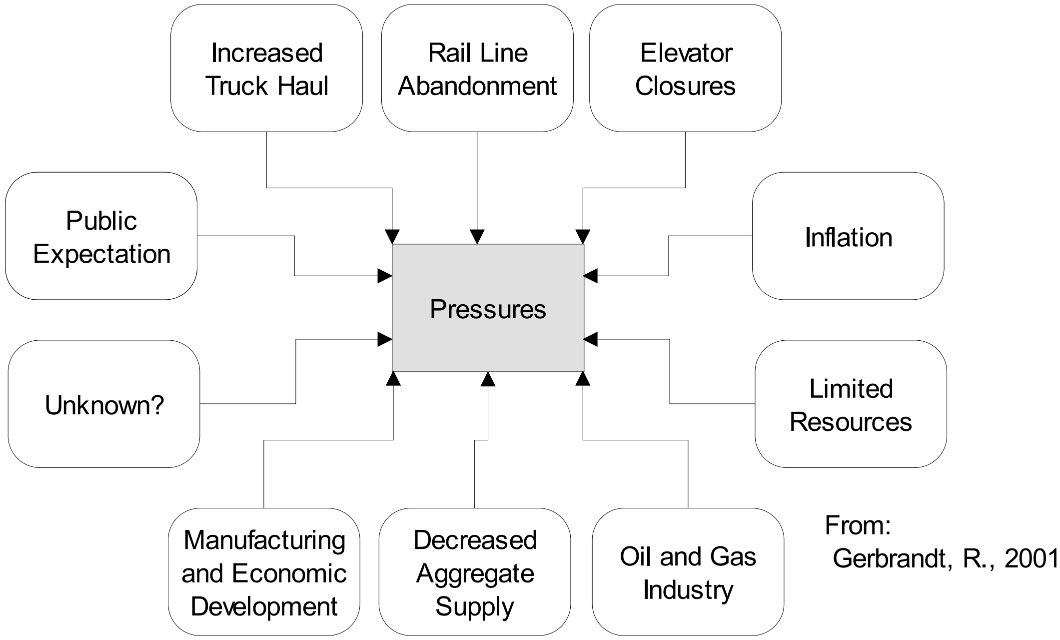


FIGURE 1.5 PRESSURES ON THE SECONDARY SYSTEM

Manufacturing in rural Saskatchewan, value-added processing and the oil and gas industry have also contributed to an increase in heavy truck traffic on the highway system. A decreased supply of aggregate has also contributed to making building and strengthening subgrades and structures more expensive than in the past. These pressures have affected TMS highways because they have not been built to handle heavily loaded trucks, unlike structural highways. SHT knows, from historical performance of the TMS network, that it can continue to maintain these low-volume highways as dust free, mud free surfaces if it can minimize the number of heavily loaded trucks (Gerbrandt and Warrener 2001). Based on this observed data, only roads that experience a high number of heavily loaded trucks need to be strengthened. Current and future pressures will continue to contribute to the deterioration of the TMS highway system until improved management solutions and more money are available for the secondary highway system.

The approximately 8,375 km of TMS highways constructed in Saskatchewan have generally performed well under car and light truck traffic. In 1995, total truck traffic on TMS roads was estimated at 104 million kilometres (SHT 1996). This is two to three times the vehicle-kilometres of truck travel when these roads were being introduced on a widespread basis (Ray Barton Associates 1998). However, under recent increases in heavy truck traffic, maintenance efforts have had to increase considerably. During the period 1993-94 to 1996-97, the annual amount spent on TMS roads has varied only slightly between $17.0 and $17.7 million per annum. In 1997-98, this amount was increased to $19.7 million. However, there was an overall deterioration in condition between 1994 and 1997 (Ray Barton Associates 1998). In addition, heavy truck loadings during the spring thaw period often result in significant road damage and increased pressure on maintenance crews to repair failures. Because much of the secondary system was not constructed to a structural standard, once surface breaks occur, failure is often quick and quite severe under repeated commercial truck loadings.

Freeze-thaw cycles have a major impact on TMS road performance. In the spring, the road thaws from the surface downward. Because there is no provision for drainage under the thawing mat, observations have shown that moisture accumulates below the mat, weakening the subgrade. If the subgrade is wet, traffic can induce rutting in the wheel paths, which leads to failure. As well, viscoplastic softening induces strain gradients in the mat causing the oiled surface to crack until pieces pick out from the surface. An extreme case of this observed process is shown in Figure 1.6.

FIGURE 1.6 TMS FAILURE IN SASKATCHEWAN

The strength of subgrade soils in Saskatchewan is highly sensitive to water content. As a result, the strength of TMS and roads typically varies by a factor of six to ten throughout the year depending on the time of year and the amount of moisture in the subgrade (Clifton Associates 1998). Dr. E. K. Sauer suggests that when the subgrade is dry the road can carry thousands of passes by loaded axles before failing; but when wet, even as few as ten loaded axle applications can result in failure (Clifton Associates 1998). Unfortunately, patching spring breaks is a stop-gap maintenance treatment at best and does not structurally improve the road. Preservation costs of many TMS and thin granular pavements can be as high as $14,000/km/year, as recorded in the SHT Area Maintenance tracking workbook (SHT 2000). When annual preservation costs are high and preservation efforts will not decrease because of continued pressures, the section of highway should be structurally strengthened or reverted to gravel to reduce life-cycle maintenance costs.

SHT has developed standards that are to be used to determine whether a highway is to be gravel or dust-free. To determine whether a highway is to be gravel or dust-free, SHT uses traffic volumes as the indicator. If the average annual daily traffic (AADT) values are below 150 vehicles per day, the standard is a gravel surfaced highway. If the AADT is above 150 vehicles per day, the highway is to be a structural, dust-free highway (SHT 1991).

When a TMS highway experiences increases in truck traffic or other pressures, and begins to show sign of deterioration, SHT must consider strengthening or some other strategy, based on SHT standards. The identified project may vary in length from being only a section of highway a few kilometres long between a grain terminal and a primary highway or may be a longer section of highway involving tens of kilometres that is showing signs of deterioration. Since the increase in pressures on the TMS highway system, SHT has not been able to meet all standards or a minimum level of service because of the constrained budget and high cost of conventional strengthening strategies.

The conventional method of strengthening TMS highways involves placing granular material on top of the existing road to get drainage of moisture under the surface and increased strength from the granular material. Road strengthening costs using SHT conventional methods for the TMS road system range from \$90,000/km for a 150 mm granular base overlay and double seal to \$250,000/km for widening the road and a granular base overlay and double seal. Two factors that dramatically affect the range of costs are whether or not the road needs to be widened and the haul distance of the granular material. Highway sideslopes have to be widened when granular material is added to the structure to maintain the top width and provide support for the structure, as illustrated in Figure 1.7. As well, if current sideslopes are steeper than 4:1, additional widening is required so SHT standards are met.

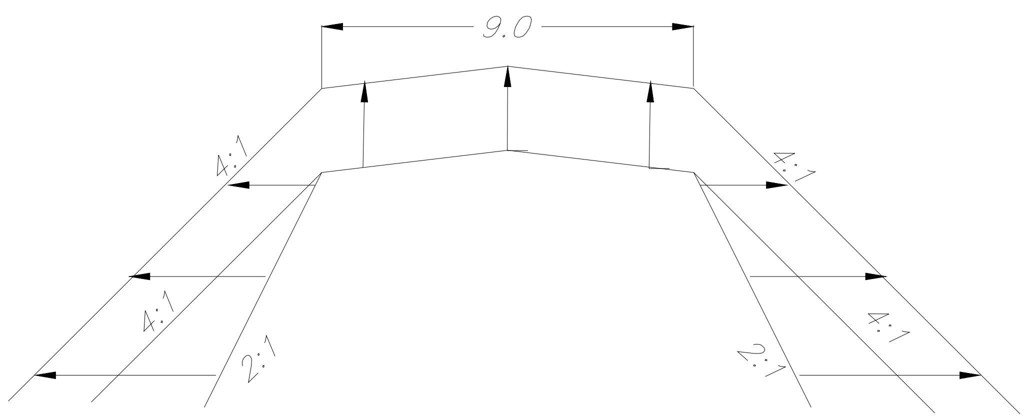


FIGURE 1.7 CONVENTIONAL STRENGTHENING METHOD

Because many TMS highways typically accommodate less than 500 vehicles per day, the necessary investment required to strengthen many Saskatchewan TMS highways is not justified based on traffic volumes. However, many secondary highways are experiencing high percentages of truck traffic, especially in high grain yielding areas and the areas where the oil industry is active, which puts disproportionately high number of large truck loadings on non-structural roads. For example, Highway No. 21 north of Unity has traffic volumes near 500 vehicles per day with truck volumes as high as 30% (SHT 2001a). This is attributed to two inland grain terminals in Unity and commercial trucking activities in support of the oil and gas fields in the region. With the seriously constrained budget, high cost of conventional treatments, and the increasing pressures, SHT has not been able to maintain the TMS highway system to acceptable standards.

The significant deterioration of the TMS road system over recent years, the lack of alternative cost-effective solutions and inadequate funding have contributed in some cases in making some TMS highways unsafe for motorists. Figure 1.8 illustrates the difference between motorist derived revenues and SHT expenditures between 1988 and 2002 (CAA 2001). Motorist Derived Revenue represent that proportion of revenues from the operation of motor vehicles and sale of taxed fuel, including the portion of fuel taxed but not consumed on provincial roads such as aviation and railway fuel. It does not include federal initiatives and programs that are not motorist derived. Between the period of 1991 and 2001, the difference between revenues and expenditures was approximately \$2.3 billion dollars (CAA 2001). The largest discrepancy between motorist-derived revenues and SHT expenditures was \$300 million in 1997. In 2001, the SHT budget reached an all-time high of \$317 million dollars. Even with the slight increase in the highway budget, years of inadequate funding on the secondary system coupled with present pressures on the system have forced SHT to develop and implement more cost-effective and sustainable methods to manage and preserve low-volume roads.

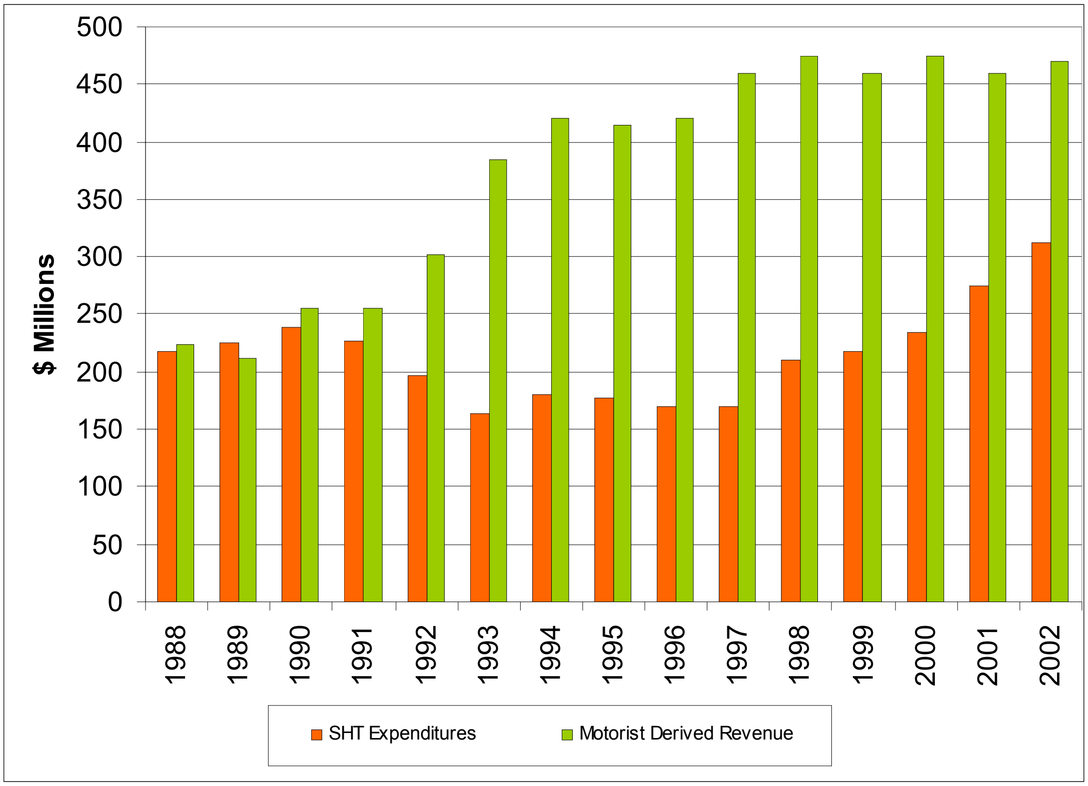


FIGURE 1.8 MOTORIST DERIVED REVENUES AND SHT EXPENDITURES

With the continued deterioration of the TMS system because of the constrained budgets and increasing pressures, there has been a need to develop strategies for TMS highways that are more cost-effective. In the past when TMS highways needed to be strengthened, SHT upgraded the road with conventional base course overlay methods. If funding was not available, the road was either left as is or reverted to gravel; although, neglecting to repair the road did not satisfy the needs of the users or meet SHT standards. The Road Science Program within SHT identified the need to develop more cost-effective strengthening strategies using science and technology and with the University of Saskatchewan, sent an individual to the University of Texas A&M to learn and bring back to Saskatchewan science and technology in the highway construction area. This research has provided mechanical and chemical stabilization methods to strengthen the subgrade and is now being used in Saskatchewan. Full Depth Chemical Strengthening (FDCS) has been widely used in Saskatchewan in the last few years and will be the focus of the example in Chapter 5.

By being able to strengthen the existing subgrade, SHT is able to “build down” instead of having to “build up” with the conventional method (Gerbrandt et al. 2000). For example, the in-situ subgrade can be strengthened with alternative binders instead of having to strengthen the road using the conventional method of adding granular material on top of the road. The alternative binders induce increased shear and tensile strength in the in-situ subgrade. As illustrated in Figure 1.9, when the structure is strengthened “building down”, TMS highways do not have to be widened to accommodate granular material to maintain top widths and sideslopes.

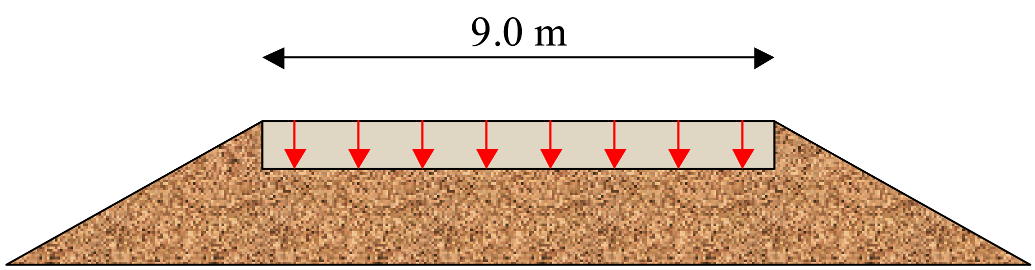


FIGURE 1.9 IN-SITU STRENGTHENING

SHT has also been working with local communities and Rural Municipalities to develop an innovative and a cost-effective method that exceeds SHT standards for preserving TMS highways. The method that has been developed is a management method of restricting the allowable vehicle weights on TMS highways to 8,000 kg and re-routing heavy trucks to municipal roads.

Saskatchewan's municipal local or rural road network consists of approximately 172,600 kilometers sub-divided into four types of classifications. The Primary Grid and Grid Systems total approximately 56,000 kilometers with the remaining 116,600 kilometres Main Farm Accesses and Local Land Accesses. The Primary Grid and the Grid System have been built to handle heavily loaded trucks and are being used to route the heavily loaded trucks off the TMS highways. Instead of reverting the TMS to gravel with a motor grader or roto-mixer, it remains a dust-free surface for lighter vehicles and heavy trucks are routed on the municipal gravel system. If SHT can analytically show that it is more cost-effective to maintain the dust-free surface and route heavily loaded trucks on municipal roads, SHT standards are met or even exceeded if the traffic volumes are below 150 vehicles per day.

With these new strategies that have been developed and the strategies that have been used for years, there is a need to develop an analytical tool that has the ability to analyze agency and road user costs over a life-cycle to determine the lowest cost strategy. However, with new cementitious strengthening methods, there is uncertainty regarding their likely service life, which in turn affects the life-cycle costs for such strategies. The question might be re-phrased as: "how long must the FDCS last to be equivalent to the Conventional strengthening method?" Therefore, there is a need to develop a framework capable of determining the lowest cost strategy of meeting SHT standards while minimizing agency and user costs. Further, because of the uncertainty related to actual service life for these new methods there is a need to quantify the effect of this uncertainty upon estimates of life-cycle costs.

1.2 OBJECTIVE

The objective of this research is to develop a project level analysis framework capable of determining the management strategy that minimizes life-cycle agency plus user costs while meeting or exceeding SHT road surface and road structural standards.

1.3 SCOPE

SHT has road surface and road structure standards that are a function of the total number of vehicles (Average Annual Daily Traffic) based on the construction year (SHT 1991). Table 1.2 illustrates the strategies that are considered in the evaluation. Two steps are needed to model the problem; the first step is to determine the SHT standard, and the second step is to determine the lowest cost strategy that meets or exceeds the predetermined standard.

TABLE 1.2 SHT STANDARDS AND MANAGEMENT STRATEGIES

AADT	< 150 vehicles per day	> 150 vehicles per day
Strategies being considered (based on SHT standards)	Gravel Reversion Status Quo Municipal Partnership Alternative Conventional	Status Quo Alternative Conventional Municipal Partnership

The following definitions will be used for the strategies from Table 1.2:

- Gravel Reversion- process of reverting the TMS from an oil surfaced highway to a gravel surfaced highway.

- Status Quo- leaving the highway as is. Because of fiscal restraints and other priorities on the highway system, agencies may choose to do nothing, even though existing conditions do not meet standards.
- Municipal Partnership- restricting the maximum allowable vehicle weight on the TMS highway to 8,000 kg and using municipal roads to accommodate the heavy trucks.
- Alternative- the new methods of strengthening the highway using mechanical or chemical stabilization. The focus of this research is FDCS because of the importance of this method in Saskatchewan at this time. However, there are other alternative strategies and they are discussed in Chapter 3.
- Conventional- this is the traditional method of placing granular material on the existing road to improve strength.

To determine the total cost, user and agency costs, as shown in Table 1.3, are included and are described in more detail in Chapter 3. The AADT is assumed to remain constant between the strategies; however, a growth rate for traffic is used for predicting the AADT over the lifetime of the strategy. This approach is taken because SHT uses this method in their surfacing designs (SHT 2001b) and does not vary traffic volumes between surfacing alternatives. User time costs are not included in User Costs because delays associated with congestion are not an issue in rural Saskatchewan. Third Party costs like noise costs are beyond the focus of this research.

TABLE 1.3- AGENCY AND USER COSTS

MINIMIZE USER COSTS	MINIMIZE AGENCY COSTS
-vehicle operating cost	-construction cost
-accident cost	-maintenance cost

Restricting allowable vehicle weights to secondary highway weights, rather than allowing the higher primary weights, impose an additional cost on road users but is not being included in this research. It is very difficult to estimate the additional transportation cost to road users because trip distance and logistics for trucks must be known and there is no method at this time to estimate costs. However, the cost savings to the transportation company could be significant. For example, by allowing primary weights for a 5-axle truck and trailer combinations on rural road systems, transportation user costs could be reduced by approximately 15%; however, agency costs would likely increase.

1.4 METHODOLOGY

Based on the literature review and consultation with the advisory committee, the following methodology was developed.

(i) Conduct a literature review so the contributions that have been made in this area by other researchers can be documented and built upon in this research.

(ii) Describe SHT standards as they relate to TMS highways

(iii) Describe the four management strategies for TMS highways.

(iv) Develop a model to calculate life-cycle road user and road agency costs. Define and describe the model inputs.

(v) Apply the analytical framework to a Saskatchewan project to demonstrate the process.

a) Determine the SHT standard for the example.

b) Determine life-cycle user and agency costs using the model.

c) Undertake a sensitivity analysis to identify sensitive variables.

d) Use probabilistic modeling to quantify implications of uncertainties.

(vi) Provide a summary and conclusions.

(vii) Possibilities for future work.

1.5 LAYOUT OF REPORT

Chapter 1 provides an introduction to the research with the background, objectives, scope and methodology. Chapter 2 provides a brief history of economic analysis for highway projects, a description of agency and user costs, and similar types of analysis. Chapter 3 provides an in-depth explanation of the strategies. SHT standards and a description of the analytical framework and model are discussed in Chapter 4. An example to demonstrate and apply the model is given in Chapter 5. Chapter 6 presents the research summary and suggests directions for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 BACKGROUND

The study of the economy of highway improvement dates back to the early 1920s. In the earlier days (1920-42) of highway construction, the emphasis was placed on design for the lowest construction cost. In 1952, the American Association of State Highway Officials (AASHO 1960) published a guide titled *Road User Benefit Analyses for Highway Improvements*. Although agencies stated that this guide needed considerable improvement, it was a substantial step forward in recognizing benefits in highway economic analyses. Curry and Haney (1966) of the Stanford Research Institute further developed the work done earlier by AASHO (1952). Their research and guide to analyses considered the effects of highway improvements on the highway agency, in terms of added construction and maintenance costs for improved highways, and on the highway users, in terms of dollar benefits due to reductions in vehicle running costs, accidents, and travel times.

Winfrey (1969) recognized that most analyses evaluate only the economic feasibility of alternatives. However, he developed concepts, principles, and standards for economic analysis and acknowledged that the final decision process goes past the strict scope of the economic analysis. His research recognized that the decision process reaches much further than a simple economic analysis of alternatives and includes social, economic, political, community, and personal aspects. He also stated that, since 1955, highway engineers have been interested in, but have not yet included in their analyses, the cost of motor vehicle running cost with their highway design. The cost of operating vehicles on the highways, as well as discomfort and inconvenience to the users, was often neglected. This research contributed to the early development of highway economics.

Hindley (1971) stated that the main factors to be taken into consideration in highway economic analysis are the cost of not having an improved road, measured in journey time, accident rate, the comparative vehicle running costs, and the return on capital investment. He also noted that there were two distinct elements of cost. The first was the cost of construction, amortised over an analysis period, maintenance, and land acquisition. Secondly, he stated there is the cost of using the roads. His research showed that the direction of economic analysis was expanding beyond road agency costs.

In the 1970s, life-cycle cost analysis (LCCA) was emerging as good practice. The Federal Highway Administration (FHWA) stated that LCCA is a technique that builds on well-founded principles of economic analysis to evaluate the overall long-term economic efficiency between competing alternative investment options (1998). Robinson (1985) suggested that in the absence of full quantifiable benefits, such as reduced accidents and opportunity costs, it seems reasonable that the economic evaluation of major projects should be based on minimising total transport costs.

Researchers have also recognized that because of uncertainty in decisions, sensitivity analyses and probabilistic modeling should be undertaken to acknowledge and explicitly model the uncertainty and risk. However, probabilistic modeling is not as well understood as deterministic modeling. Probabilistic modeling has been recognized since the 1970s for the prediction of pavement deterioration over time (Darter and Hudson 1973). Although progress has been made in the development of probabilistic modeling of pavement performance, the applicability of many existing probabilistic models is limited to local or regional pavement networks (Ningyuan 1997). The FHWA (1998) suggested that, as a minimum, a sensitivity analysis should be included. However, it recommended that a probabilistic approach be undertaken so that the areas of uncertainty can be modelled.

Economic analysis for highway project evaluation has been evolving for years and is discussed in Section 2.2. Section 2.3 discusses the literature regarding agency and user costs. To conclude this chapter, research and models that accomplish similar goals to this research are summarized.

2.2 TYPES OF ANALYSIS

As discussed earlier, there have been years of research in the area of engineering economic evaluation. Agencies use different tools to evaluate decisions; however, most agencies only evaluate monetary issues. Some of the more common economic techniques used to evaluate projects include LCCA and benefit-cost analysis. If the agency is evaluating more than just cost, a multi-attribute decision framework must be used (Clemen 1996). Economic evaluation has evolved over the years.

LCCA is an economic analysis process of incorporating initial and discounted future agency, user, and other relevant costs over the life of investments. All costs are discounted to the present and a present value comparison is made. Alternatively, another method of comparing alternatives is with the equivalent uniform annual cost (EUAC) method. Instead of comparing the present worth of alternatives, an annual cost comparison is made by transforming present worth values into annual worth values. When an agency looks at the cost of alternatives over a lifetime, difficulties usually arise because alternatives have different life expectancies. To accommodate this, when using the present worth method, a salvage value must be used at the end of the life-cycle so that a fair comparison can be made. Instead of using a present worth comparison and having to predict a salvage value, the EUAC method is often used. By doing this, the issue of salvage value is avoided.

LCCA attempts to identify the best value (the lowest cost that satisfies the performance objective being sought) for investment expenditures (FHWA 1998). The life-cycle analysis for investment planning, new pavement design, overlay design, and selection of pavement type has been a recognized approach since the 1970s (Uddin and George 1993). Freer-Hewish (1990) stated that technical and managerial improvements in design, construction and maintenance of roads, cannot be fully accepted without a realistic total cost evaluation of their economic significance. In recent years there has been greater emphasis within transportation agencies to use life-cycle costing in decision making. Life-cycle costing allows transportation agencies to better estimate the costs involved in pavement maintenance and rehabilitation programs by taking into account the economic assessment of different rehabilitation alternatives on the basis of all significant costs expected over the economic life of each alternative in equivalent dollars (Zimmerman and Grogg 2000). LCCA provides the agency with a comparison of the total costs of alternatives over a lifetime.

In the late 1980's, SHT used the Highway Design and Maintenance Standards Model (HDM-III) to develop a set of pavement performance models as SHT realized the importance of considering user costs with life-cycle costing as part of highway investment decisions (Bein et al. 1989). The development of a rational annual work program and budget for roads and highways in the jurisdiction of a public work agency requires life-cycle analysis of all agency and user costs. This approach can lead to cost-effective investment planning of new roads and to maintenance, rehabilitation, and reconstruction work programming for the existing network (Uddin and George 1993). They also believed that the life-cycle approach based on agency and user costs is applicable in project-level decisions in establishing priority ranking of candidate roads and in selecting competing maintenance, rehabilitation, and reconstruction treatment alternatives.

Benefit-cost analysis is another economic analysis tool. In benefit-cost analysis, once the alternatives are determined, a planning period is chosen and the monetary benefits and costs over the planning period are established. The benefits and costs are discounted to an EUAC or present worth, and then the benefits are divided by the costs. Normally, the alternative with the highest benefit-cost ratio is selected, as long as it is greater than one. Benefit-cost analysis has long been applied to assess the economic soundness of public decisions. The pros-and-cons of this approach have been discussed extensively and the applicability has often been subject to strong criticisms, both from methodological and ethical perspectives (Beinat and Nijkamp 1998). Difficulties arise when defining benefits as actual benefits or as negative costs and vice-versa. When benefits are not clear, analyses with these benefits included will skew results. However, benefit-cost analysis is used and is recognized as an effective economic analysis tool when applied correctly.

Zimmerman and Grogg (2000) stated that costs that are included in economic analyses could be reported in terms of either nominal or real (constant) dollars. Real-dollar values reflect dollars that have the same, or some constant level, of purchasing power over time. With this definition, an agency representing future costs as real dollars would report the cost of conducting some type of activity in the future as equal to the cost if the activity were performed today. Real discount rates reflect the true time value of money with no inflation premium. Nominal-dollar values, in contrast, reflect dollars whose purchasing power fluctuates over time due to inflation. Nominal-dollar values are used by agencies interested in building anticipated increases in price caused by inflation in their cost estimates. When completing an analysis an agency must decide whether it is appropriate to use either real or nominal dollars for their purposes.

2.3 AGENCY AND USER COSTS

More than 10 billion dollars are spent each year on highway construction, maintenance and administration by governments in the developing countries of Africa, Asia and Latin America (Watanatada et al. 1987). In the industrialized economies of Europe, North America, and Japan, the total is something more than 10 times as great.

These numbers are impressive, but it must also be noted that the costs borne by the road using public are typically 8 to 10 fold those borne by the government.

To determine the cost of a highway project, both agency and user costs should be taken into account so that the total cost is realized. Agency costs are the costs borne to the agency to construct and maintain a road. Agency costs are easily accounted for because budgets are monitored and measurable. It is convenient for agencies to only include their costs in analyses because these are the only costs for which they are responsible. User costs are harder to measure and do not affect agency budgets directly. User costs should be included in analyses because minimizing both user and agency costs will provide a better economical return to society than just minimizing agency costs. As mentioned earlier, third party costs like noise costs are not included in this research.

The Organization for Economic Co-Operation and Development (OECD)(1994) stated that the commonly accepted objective of road resource allocation is the minimization of agency plus user costs over the lifetime of the facility. Road user costs include vehicle operating, accident, and time costs incurred by users of the road. Vehicle operating costs (VOC) are the major component of user costs. Accident costs are based on accident rates and when a road is improved, accident rates should be lowered, thus lowering the cost of accidents on highways. Values have to be assigned for types of accidents and accident rates have to be predicted for upgrade values. User costs also consist of time costs; however, this research does not include time costs because travel delay costs are not an issue in rural Saskatchewan and are generally more of a concern in urban centres and on high-volume roadways where delays associated with congestion are of concern. Models are available to predict user costs; however, agencies must ensure the model is applicable to their highway network.

There are many user cost models available to predict costs on a highway. Some of the major models available around the world have been identified by Bein (1993). They include: the Texas Research and Development Foundation (TRDF) model (Zaniewski et al. 1982), the Australian Road Fuel Consumption Model (ARFCOM) (Biggs 1988), the Swedish VETO model (Hammarstrom and Karlsson 1987), the American Highway Economic Requirements System (HERS) (Federal Highway Administration 2000), the World Bank Highway Design and Maintenance Model (HDM-III) (Watanatada et. al. 1987), the Canadian Highway User Benefit Analysis Model (HUBAM). Bein (1993) evaluated the state-of-the art VOC models for the purpose of North American road infrastructure planning needs. His research concluded that only the mechanistic models VETO, ARFCOM and partly HDM-III are transferable to North American conditions. Berthelot (1992) developed a mechanistic model focused on vehicle operating costs in Western Canada. Figure 2.1 illustrates the vehicle operating costs that he defined in his research.

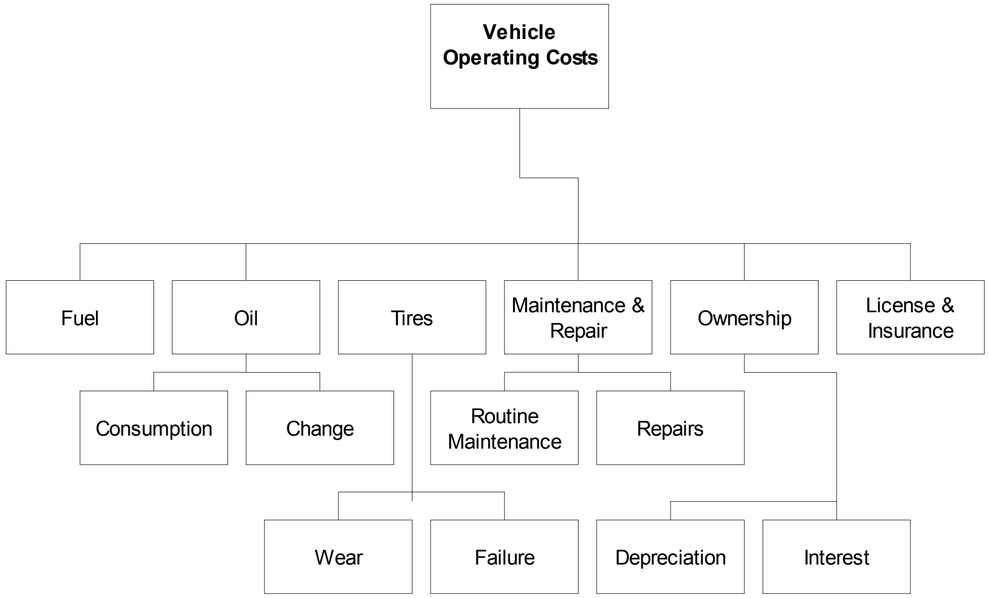


FIGURE 2.1 VEHICLE OPERATING COSTS

Sparks & Associates Ltd. (SAL) developed a road user cost model that would assist SHT when conducting vehicle operating cost studies (Sparks & Associates Ltd. 1993). From this study, SAL determined that the Berthelot model (Berthelot 1992) is most appropriate for Saskatchewan's needs. Since 1993, SHT has been using the Berthelot model for predicting VOC. For the purpose of predicting VOC for this research, the Berthelot model will also be used.

2.4 SIMILAR RESEARCH

In 1968, the World Bank commissioned the Massachusetts Institute of Technology (MIT) to construct a road project appraisal model (Watanatada et al. 1987). The resulting Highway Cost Model (HCM) produced by MIT was a considerable advance over other models used for examining the interactions between road work costs and VOC (Moavenzadeh et al. 1971). Following this, the World Bank and Transport and Road Research Laboratory (TRRL) undertook a major field study in Kenya to investigate the deterioration of paved and unpaved roads and from this, developed the Road Transport Investment Model (RTIM) (Robinson et al. 1975). In 1976, further developments to HCM produced the first version of the Highway Design and Maintenance Standards Model (HDM) (Harral et al. 1979).

Further work was done and in 1982, the TRRL Overseas Unit introduced the total life-cycle cost Road Transport Investment Model (RTIM2) for developing countries (Parsley and Robinson 1982). In 1985, it was replaced with the newer and more sophisticated HDM-III model from the World Bank (Watanatada 1987); the conceptual model is shown in Figure 2.2. The World Bank's HDM-III model has the ability to predict pavement deterioration and vehicle operating costs over an extended analysis period in which these are dependent on the pavement design standards and the maintenance policies applied to the pavement (Riley et al. 1994). The model facilitates economic comparisons between many alternatives, taking into account the interrelation between construction standards and maintenance operations in determining the quality of a road link and the interrelation between road quality and the operating costs of vehicles using the roads (Watanatada 1987).

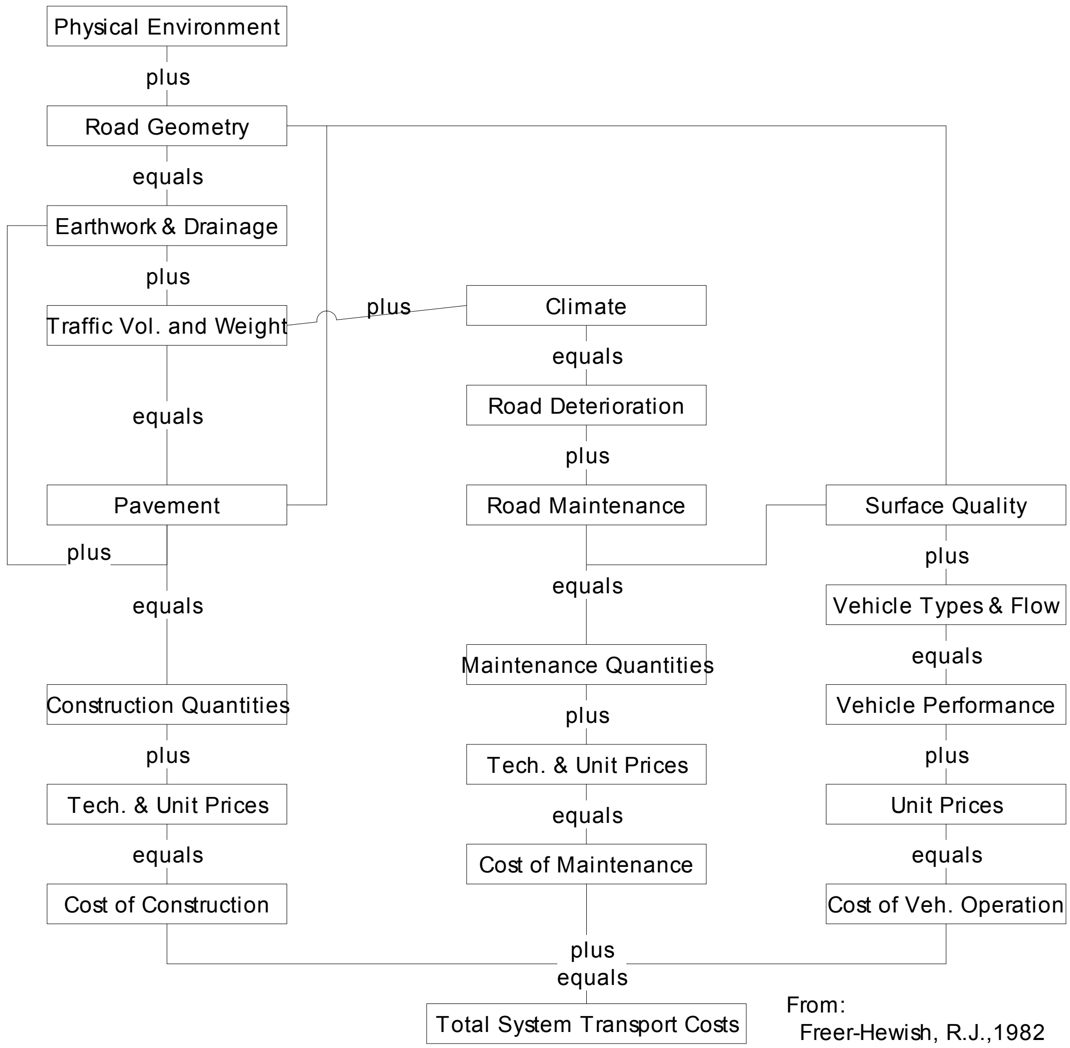


FIGURE 2.2 CONCEPTUAL DIAGRAM OF HDM3

In 2000, after two decades of successful modeling with the Highway Design and Maintenance Standards models, the World Bank released its successor to HDM-III, the Highway Development and Management Tool (HDM-4) (World Road Association 2000). HDM-4 deals with the highway management process as a function of Planning, Programming, Preparation and Operations. The highway management process as a whole can, therefore, be considered as a cycle of activities that is undertaken within each of the management functions of Planning, Programming, Preparation and Operations, as shown in Figure 2.3.

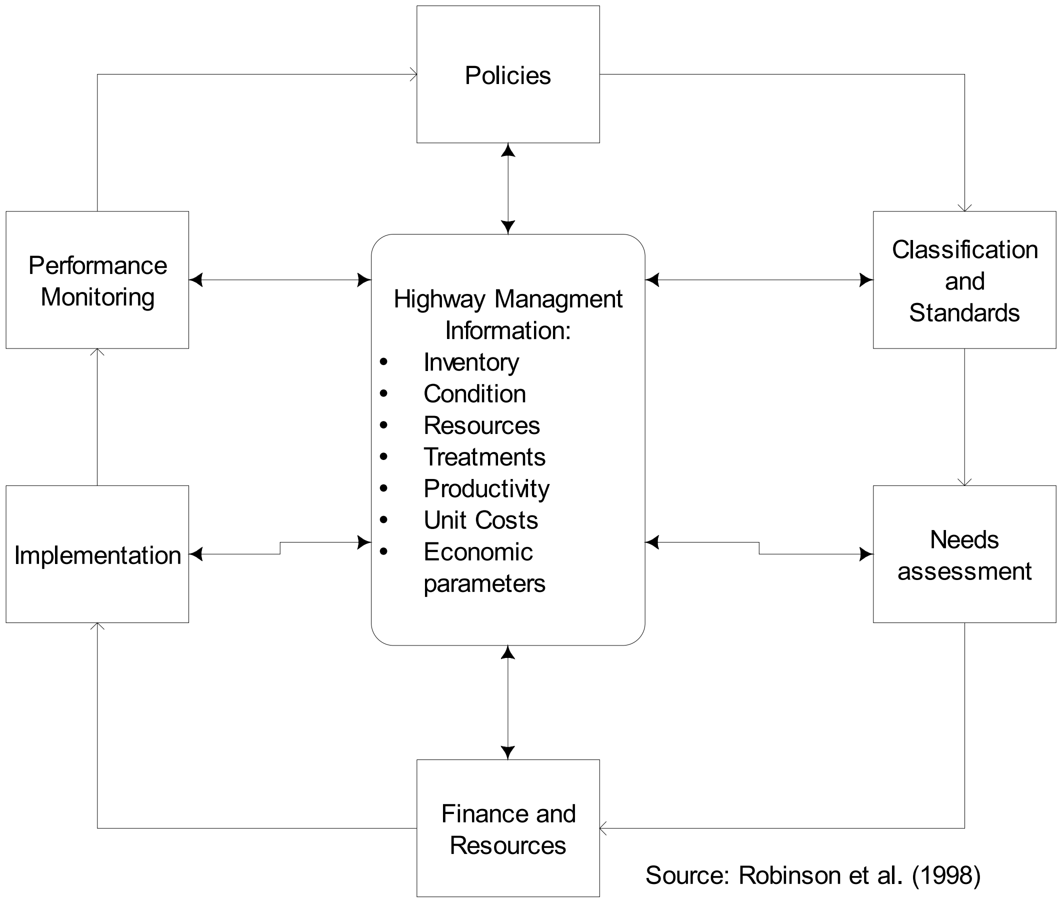


FIGURE 2.3 HIGHWAY MANAGEMENT CYCLE

HDM-4 models the whole highway management system and is very data intensive. Planning and Programming modules are the analysis of the road system as a whole, typically requiring network level medium to long term strategic planning. Project analysis, in HDM-4, is concerned with the evaluation of one or more road projects or investment options. The following issues can be addressed to estimate the economic viability of the project:

- The structural performance of road pavements.

- Life-cycle predictions of road deterioration, road works effects and costs.
- Road user costs and benefits
- Economic comparisons of project alternatives

Because HDM-4 is so broad and has numerous capabilities and options, it is extremely data intensive. Because SHT has a pavement management system, HDM-4 is too big of an investment in time and money for SHT needs.

All the Canadian Provinces were contacted to determine what type of analysis they are completing on their low-volume highway system. The results are summarized in Table 2.1.

TABLE 2.1 CURRENT PRACTICE BY PROVINCE

	Type of Analysis for Low-Volume Roads
British Columbia	Project by project analysis
Alberta	Alberta Pavement Design Guide Nothing specific for low-volume roads
Manitoba	No response
Ontario	Life-cycle cost analysis without user costs HDM-4
Quebec	No response
Maritimes	No response
North West Territories	No program in place

CHAPTER 3 MANAGEMENT STRATEGIES

3.1 SHT DESIGN STANDARDS

As discussed in Chapter 1, the increasing truck traffic on the TMS highway system has triggered many projects that require either strengthening or gravel reversion. The creation of new management strategies, if found to have a lower total cost for a project while still meeting the needs, will allow SHT to provide more projects on the TMS highway system for the same budget. Once a project is identified, the first step is to determine SHT standards so the strategies that meet the standard can be identified.

SHT determines the surfacing and structural standard based on traffic volumes (SHT 1991). When traffic volumes are less than 150 vehicles per day, the standard for the highway is a gravel-surfaced highway. When traffic volumes are more than 150 vehicles per day, the standard is a structural, surfaced highway.

As illustrated in Table 1.2, there are up to four strategies that meet SHT design criteria, depending on traffic volumes. Status Quo is included in the evaluation with the strategies, even though standards are not being met, because the Agency always has the choice of doing nothing. The four strategies, as stated earlier, are Conventional, Alternative, Municipal Partnership, and Gravel Reversion. The strategies and descriptions in this research are described in terms of SHT practices. Other jurisdictions may have other strategies, but that is beyond the scope of this research.

3.2 CONVENTIONAL

The Conventional management strategy for a low-volume highway, with traffic volumes between 150 and 700 vehicles per day, is to provide a Pavement C granular structure using the Saskatchewan Design Method (SHT 2001b). A Pavement C is a 15-year designed granular structure comprising a sealed road surface. The design process consists of determining the California Bearing Ratio (CBR) of the subgrade and the traffic prediction for equivalent single axle loads (ESAL's) over 15 years. Based on the CBR value and the estimated ESAL's, a granular thickness value is obtained. This thickness is the thickness predicted to be required to support traffic over 15 years. The granular thickness consists of granular subbase and base, which is applied on top of an existing road, as shown in Figure 3.1. The maximum thickness of the base course for a Pavement C is recommended as 120 mm and a minimum total granular thickness of 300 mm. However, in cases where the subbase is unstable, the granular base course would be increased.

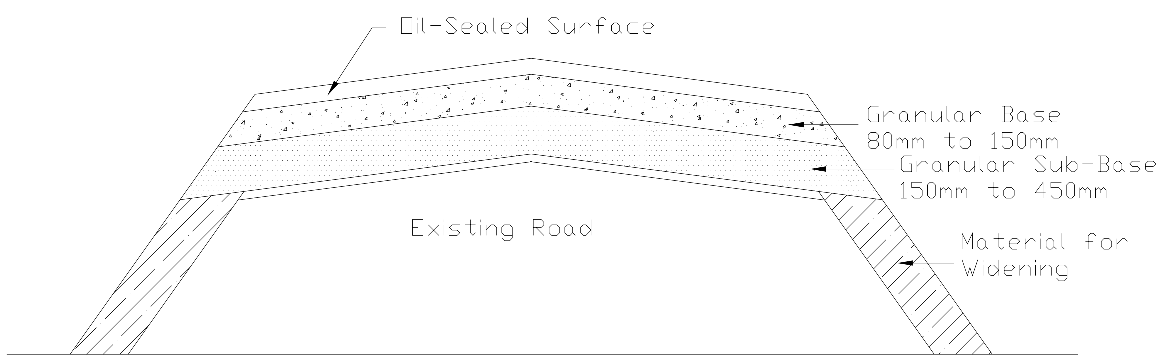


FIGURE 3.1 CONVENTIONAL STRENGTHENING

Problems occur when adding granular material to the top of the existing road structure on secondary highways. Finished top widths may be too narrow to accommodate traffic because of the 4:1 sideslopes that are required for safety and structural support. In these cases, the structure has to be widened. This process involves notching out the existing sideslopes, widening the existing road and then placing the granular structure on top, as shown in Figure 3.1. This is an expensive solution for Saskatchewan's secondary system. For example, to add 40,000 tonne/km of material for re-grading, 300 mm of subbase, 150 mm of base, and a double seal costs approximately \$200,000/km, assuming a material haul of 25 km. Alternatively, without the 40,000 tonnes of material for re-grading, the cost is approximately \$100,000/km.

Once the road is strengthened, the traveled surface is usually surfaced with a double oil seal. A double oil seal costs approximately \$20,000/km. In some cases, the surface is paved with asphalt concrete. Paving generally does not occur on the secondary system because the cost of asphalt concrete can range from \$40,000/km for a 40 mm lift to \$100,000/km for a 100 mm lift. If asphalt concrete is used, generally less granular material is used because asphalt concrete, unlike a double seal, provides added strength to the structure of the road.

The advantages of Conventional treatments include the following:

- The construction technique has been used for many years (recorded in the SHT Construction logs since 1952); therefore, the methods are well known.
- Contractors and equipment are readily available to perform the work.
- Empirical data, tests, and programs are available to predict performance.

- Specialized knowledge is not necessary because all specifications and procedures have been set out over the years.

The disadvantages of Conventional treatments include the following:

- Quality aggregate is becoming more scarce and is non-renewable.
- Construction is expensive and hard to justify (low traffic volumes).
- Re-grading is usually needed so widths can be maintained (very expensive).
- Failure may occur if there is an increase in heavy traffic and that increase was not accounted for in the original design.

3.3 ALTERNATIVE

Alternative management strategies are new and innovative techniques used by SHT in Saskatchewan to improve the strength and/or condition of the road. In the last few years, SHT has been testing these Alternative strategies, but unlike Conventional strategies, their long-term serviceability has not yet been proven. As shown in Figure 3.2, mechanical and chemical strengthening are the two types of Alternative management strategies currently being evaluated. This is not an exhaustive list, but it illustrates the types currently available to SHT.

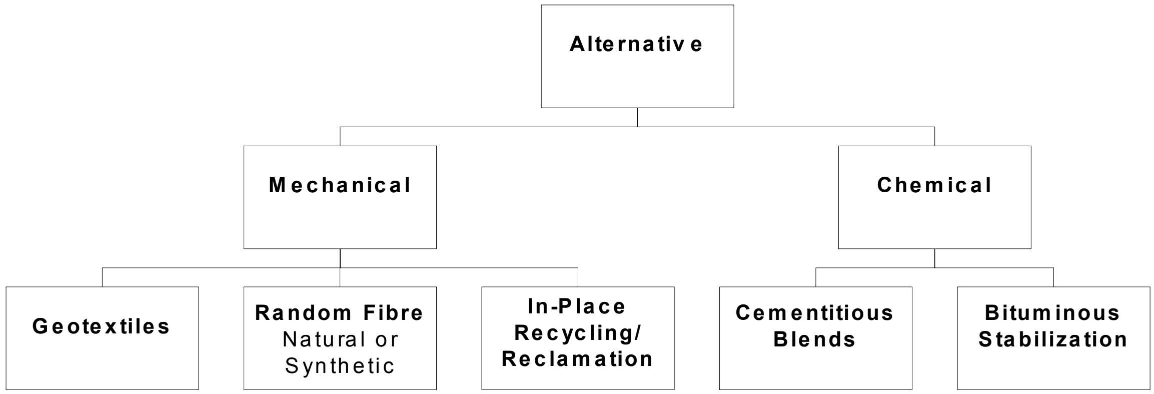


FIGURE 3.2 ALTERNATIVE MANAGEMENT STRATEGIES

3.3.1 Mechanical Strengthening

Mechanical strengthening is the process of changing the characteristics, not the material properties, of the structure by adding materials or combining existing materials. Granular stabilization with in-place recycling, geotextiles and inclusion of random fibres are described below. Although mechanical strengthening techniques have had limited applications across Saskatchewan, they will continue to be evaluated to determine long-term performance and effectiveness.

Granular stabilization with in-place recycling, or full-depth reclamation, is the process of blending in-place material and external granular materials using a reclaiming machine. The difference between full-depth reclamation and in-place recycling is that in-place recycling does not penetrate the whole depth of the granular structure while full-depth reclamation does. In-place recycling will be the term used in this research; however, it can include full-depth reclamation. This process easily allows the addition of granular material ahead of the reclaimer so that the material can be mixed with the material in the existing structure. Reclaimers typically mix to a depth of 200 to 300 mm in Saskatchewan. After being mixed, the material that exits the mixing chamber is a homogenous, well-graded material – normally having a maximum particle size of 50 mm. Figure 3.3 illustrates the process of reclaiming the existing road grade. The cost of rotomixing the in-place subgrade with the reclaimer is between \$1.00/m^2 and \$3.00/m^2. To complete the process, compaction equipment is used to key the material back in place and a motor grader is used to shape the grade. Once this process is complete, the road can be surfaced or left as a gravel structure. Granular stabilization is one type of mechanical stabilization method.

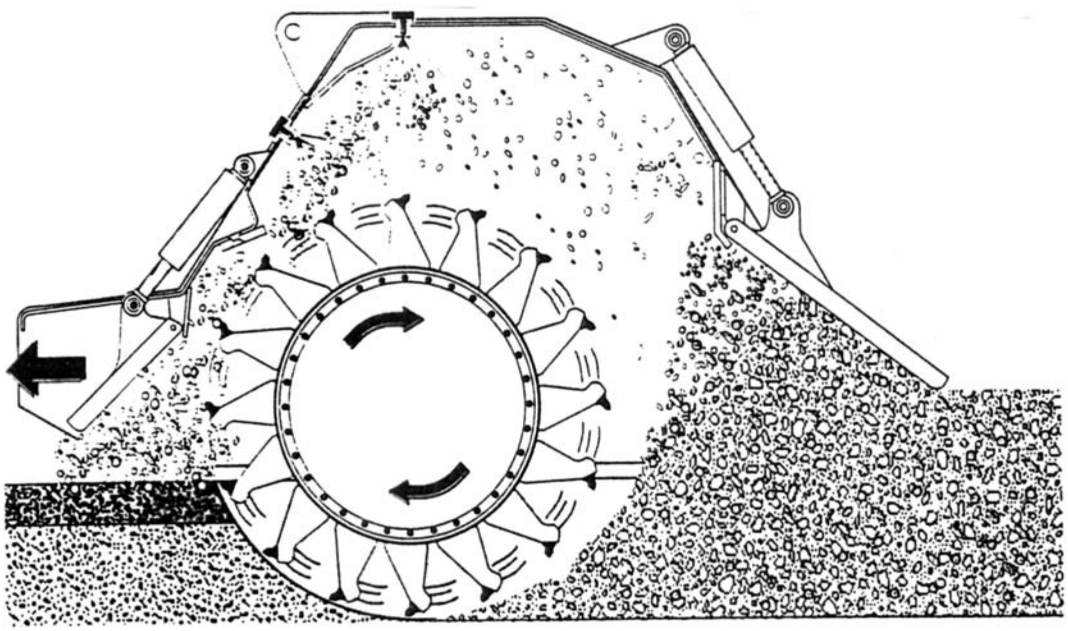


FIGURE 3.3 IN-PLACE RECYCLING OF SUBGRADE

The advantages of granular stabilization with in-place recycling are as follows:

- The process requires less granular material than conventional strengthening.
- Recycling the subgrade utilizes the existing in-place materials.
- The process eliminates surface defects and restores cross section.

The disadvantages of granular stabilization with in-place recycling are as follows:

- Contractors have limited experience in this field.
- Equipment is expensive; therefore, very few contractors have invested in it.
- SHT does not have experts within the department to lead the process.
- Granular material is needed to improve road strength.
- Long-term performance is uncertain.
- Process will fail if in-situ materials are of poor quality.

Other mechanical strengthening options include using geotextiles to stabilize the highway or adding fibres to the subgrade to change the mechanical properties of the subgrade characteristics. SHT has used geotextiles in limited applications to stabilize road subgrades. Typically, failure of a road results in contamination of high strength aggregate with weaker subgrade materials as a result of upward pumping of subgrade materials by applied loads. Introducing a geotextile into the subgrade interface can help to maintain the structural integrity of the processed aggregate. As well, on TMS highways, geo-fabrics have been placed on a thin layer of granular material on the existing structure, covered with a layer of granular material, and then resurfaced to provide strength. Geotextiles are typically a woven synthetic, and in weak subgrade situations (CBR<2), the geotextile must reinforce the subgrade as well as separate the layers (Armtec Ltd. 2001). SHT has also used fibres to mechanically strengthen the subgrade. The purpose of adding fibres, either natural or synthetic, to the subgrade is to add strength by mechanically changing the material composition of the road structure. Figure 3.4 illustrates flax straw being added to a highway subgrade using a reclaimer.

FIGURE 3.4 ADDITION OF FLAX STRAW TO THE HIGHWAY SUBGRADE

The advantages of geotextiles or fibres to the subgrade are as follows:

- Natural fibres are relatively inexpensive.
- Geotextiles work well for layer separation.

The disadvantages of geotextiles or fibres to the subgrade are as follows:

- Geotextiles are expensive.
- Contractors do not have expertise or equipment for the techniques.
- SHT does not have experts within the department to lead the process.
- Procedure is labour intensive.

3.3.2 Chemical Strengthening

Chemical strengthening is the process of adding chemicals to the highway subgrade to increase road strength. SHT has been testing cementitious blends and bituminous stabilization with in-place recycling to change the properties of the in-situ subgrade material and increase the strength. The “building down” process uses in-situ materials that are used to strengthen the road without losing the existing surface width, so that material is not needed for widening sideslopes. This process may be less expensive than Conventional strengthening methods because, in most cases, the road will not have to be widened.

One type of chemical stabilization is the use of cementitious material in the structure. Cementitious stabilization refers to stabilization using either cement or supplementary cementitious materials. Supplementary cementitious materials are mixtures of pozzolanic materials such as fly ash or pulverized blast furnace slag and lime. SHT has been using FDCS for several years on test sections and continues to expand the use. However, a detailed investigation and analysis has to take place of the existing conditions by a material expert before a decision can be made on a type of chemical stabilization. Figure 3.5 illustrates the addition of FDCS to a subgrade. The focus of the example in Chapter 5 will be with FDCS because this stabilization method has had seemingly considerable success on Saskatchewan secondary roads; however, long-term performance is still uncertain.

FIGURE 3.5 ADDITION OF CEMENTITIOUS MATERIAL TO ROAD STRUCTURE

Another form of chemical stabilization is bituminous stabilization. Bituminous stabilization is usually intended to introduce some cohesion into non-plastic materials; therefore, the process is more successful with granular material than with cohesive material. Bituminous stabilization may be carried out with the following materials:

- Cut back bitumen
- Hot bitumen
- Bitumen emulsion, either as cationic or anionic emulsion

As with cementitious stabilization, bituminous stabilization is a specialized process and requires input from experts as bituminous materials perform differently under different material conditions. Bituminous stabilization has only been used in demonstration projects in Saskatchewan to date.

The advantages of chemical stabilization are as follows:

- Increase of strength to the structure without having to raise the grade height; and therefore narrow the top width;
- Non-renewable granular materials are not needed for additional strength;
- Reclaiming eliminates surface distresses and restores cross section;
- Some chemicals are by-products of other industries.

The disadvantages of chemical stabilization are as follows:

- SHT does not have budgets to experiment with all forms of stabilization;
- High level of expertise needed;
- Long-term performance is unknown.

3.4 MUNICIPAL PARTNERSHIP

Municipal partnership refers to the Rural Road Partnership Program that is underway in Saskatchewan. Unlike Conventional or Alternative strategies, this management strategy does not strengthen the road; instead, heavy truck traffic is routed on the municipal system while light traffic, less than 8,000 kg, travels on the TMS highway. With the heavy truck traffic off of the TMS highway, maintenance and preservation costs are reduced and the surface generally deteriorates more slowly because TMS highways perform well under light traffic. The increased heavy truck traffic increases costs on the municipal gravel road, but maintenance on a gravel road is easier and less expensive than maintenance on a TMS. SHT pays the Rural Municipality for the increase in maintenance costs, so costs are not transferred from one government to another. This management strategy is an option only when there is a primary or municipal grid road available to handle the increased vehicles and loads. The Rural Road Partnership Program is an excellent way to more effectively utilize Saskatchewan's infrastructure.

SHT and a number of local Rural Municipalities have implemented projects under the Rural Roads Partnership Program. The primary goal under the initiative, as stated by Gerbrandt and Warrener (2001), is to encourage cooperation between the provincial and local governments in the delivery of improvements to effectively increase serviceability of a sustainable infrastructure. The initiative allows the provincial and local governments to provide a dust-free highway on various TMS roads while rural municipal grid roads handle the heavy truck loadings. Local transportation requirements, primarily those of local people, are addressed by utilizing both the highway network and the local rural municipal network under the Rural Roads Partnership Program. Objectives under the Rural Road Program include the following (Gerbrandt and Warrener 2001):

a) The program receives local input into managing the overall local transportation system in their respective area.
b) Saskatchewan Highways and Transportation and the Rural Municipalities have limited time and resources to adequately manage the TMS road network.
c) The program optimizes weight and route management opportunities and user safety. Implementing haul route management plans concentrates loads on specific routes. Saskatchewan Highways and Transportation and the Rural Municipalities can target resources and efforts to these roads and at the same time minimize work requirements on other routes.

d) Dust-free TMS highways allow for local light traffic, emergency vehicles, school buses and tourist traffic.

An example of the Rural Road Partnership Program is shown in Figure 3.6. As shown in the figure, Highway 342 is a TMS that has been restricted to 8,000 kg. Vehicles weighing more than this amount are required to take the designated grid road. Although this may appear to be an inconvenience for truckers, local residents are committed to this partnership because their dust free access to the community is retained, allowing their passenger vehicles, school buses, and emergency vehicles to travel on a well maintained TMS. Most farmers in the area utilize the local rural grid system while commercial truckers use the haul route.

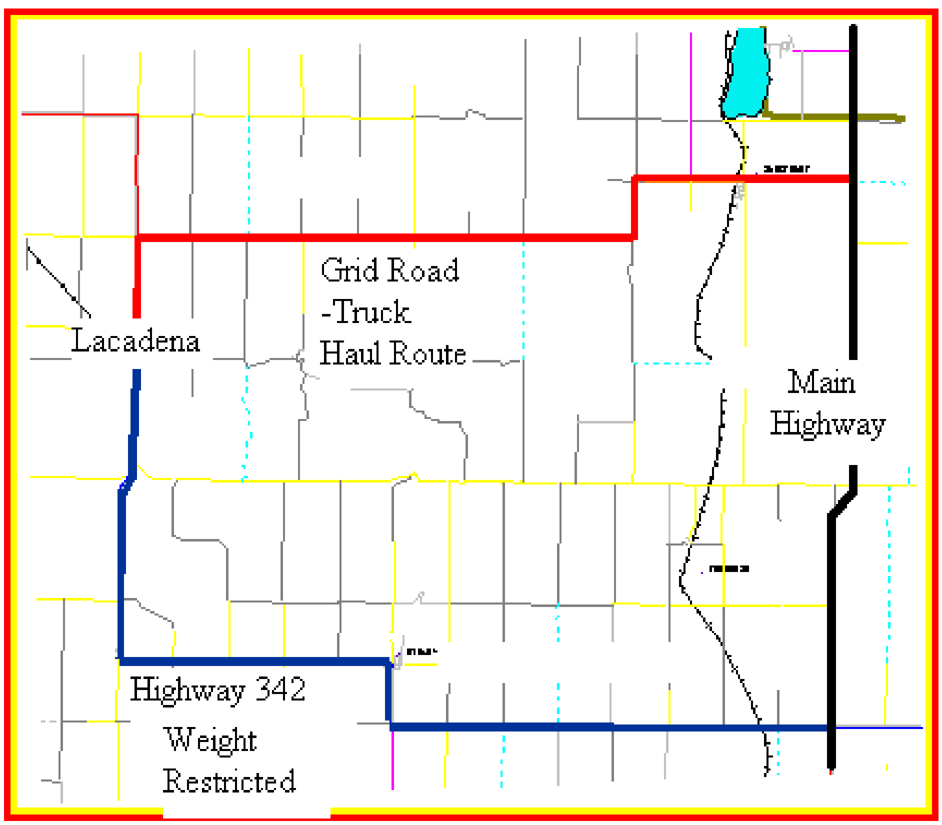


FIGURE 3.6 HIGHWAY 342 PARTNERSHIP AGREEMENT

The advantages of the Rural Road Program are as follows:

- It allows local input into transportation decisions.
- The program utilizes Saskatchewan's provincial and municipal road network.
- It is a way to preserve a TMS highway.

The disadvantages of the Rural Road Program are as follows:

- There must be a grid system in place to which to divert the heavy traffic.
- The rural municipal gravel road must be structurally adequate to handle heavy loads.
- Increases trucking costs.
- It requires that permits be issued.
- The restricted highway requires enforcement presence to ensure compliance.

3.5 GRAVEL REVERSION

Gravel Reversion is the process of reverting an oil-surfaced highway to a gravel-surfaced highway. To revert an oil-surfaced road to gravel, the surface has to be ripped or pulverized with a grader or a road reclaimer. Motor graders are relatively less expensive than a road reclaimer for gravel reversion but motor graders do not pulverize the asphalt pieces like the road reclaimer. Once the road is keyed back in place, it requires gravelling and possibly bi-annual dust-abatement chemicals near farmyards. The capital cost of reverting a TMS road to gravel is approximately \$15,000/km to \$35,000/km in Saskatchewan, based on historical costs, and maintenance costs of the reverted gravel surface will be lower than maintaining a TMS (Vemax Management Inc. 1998). Gravel Reversion is not usually a politically favourable management strategy and will cause great debate with local highway users. However, if the surface condition of a TMS gets to a point where it requires major maintenance to return it to an acceptable condition, the appropriate standard is determined, then the TMS must be strengthened, weight restricted or reverted to gravel.

The advantages of Gravel Reversion are as follows:

- Maintenance of a gravel road is easier and less expensive than on an oil surfaced highway.
- When the road gets in bad condition, it is easy to return it to its original condition by blading.
- Drivers of large trucks prefer to drive on a good gravel road than poor TMS road.

The disadvantages of Gravel Reversion are as follows:

- Gravel roads are dusty in dry weather and slippery in wet weather.
- It is politically difficult to sell to the local users.
- Gravel roads require frequent blading to maintain condition.

3.6 STATUS QUO

The option of Status Quo, or doing nothing, is always available to a road agency. Unfortunately, doing nothing does not improve highway conditions or may not meet defined standards. Even with maintenance repairs, they are low-cost, temporary, and do not alleviate the problem when the road gets to a condition that it needs strengthening. Because of the extensive highway network, maintenance crews usually have more roads to fix than time available. Status Quo provides a basis for comparison of other strategies and may be chosen, depending on the Agencies fiscal constraints, but is only a short-term solution.

CHAPTER 4 FRAMEWORK

4.1 DECISION ANALYSIS PROCESS

The decision analysis process, as defined by Clemen (1996), has been modified to model this process, as shown in Figure 4.1. The first two steps of the decision process are to determine the SHT standard that applies to the project at hand and secondly, to identify the strategies that meet the SHT standards. These first two steps were presented in Chapter 3.

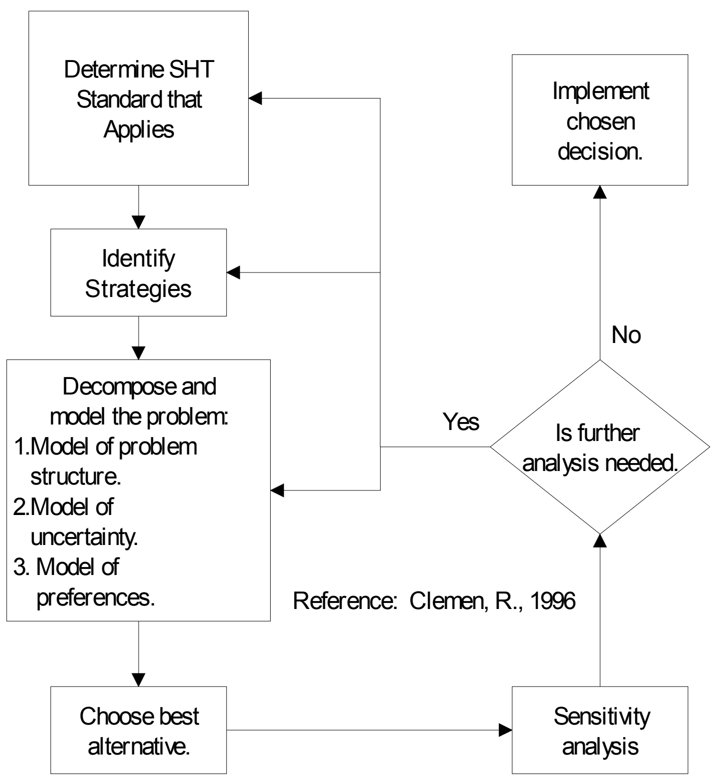


FIGURE 4.1 DECISION ANALYSIS PROCESS

The next step in the modeling process is to decompose and model the problem. To determine the total cost (agency and user), the computer programs, Decision Programming Language (DPL) (Applied Decision Analysis 1998) and Microsoft Excel were used. DPL uses influence diagrams to represent decision situations. In an influence diagram, rectangles represent decision nodes and ovals represent chance nodes. A rectangle with rounded corners is used to represent a mathematical calculation or a constant value. Information on influence diagrams and how to interpret them are contained in *Making Hard Decisions* by Clemen (1996). The completed influence diagram for the conceptual model to determine total user and agency costs is shown in Figure 4.2. Initial values were inputted into DPL. DPL then uses Microsoft Excel to calculate intermittent values; the final values for each node are exported back to DPL to determine the total costs for each strategy. Individual nodes from Figure 4.2 are explained in greater detail later in the chapter.

Once the results were obtained, a deterministic sensitivity analysis was completed to determine the sensitivity of the outcome to variations in the values of input variables. To complete the sensitivity analysis, high and low values for each variable in each node and strategy were substituted in and *DPL* calculates an expected value tornado diagram. Part of the calculation involved developing an expected value tornado diagram, which determines if any of the high or low values will affect the decision.

Once the deterministic analysis is completed, probabilistic modeling then begins. Values in the model can have probabilities assigned so that the uncertainty can be modelled explicitly. The output is an expected value, which is the probability-weighted average of its possible values. As well, the probability can be graphed as a distribution of expected values. Probabilistic modeling is demonstrated and applied in the example in Chapter 5.

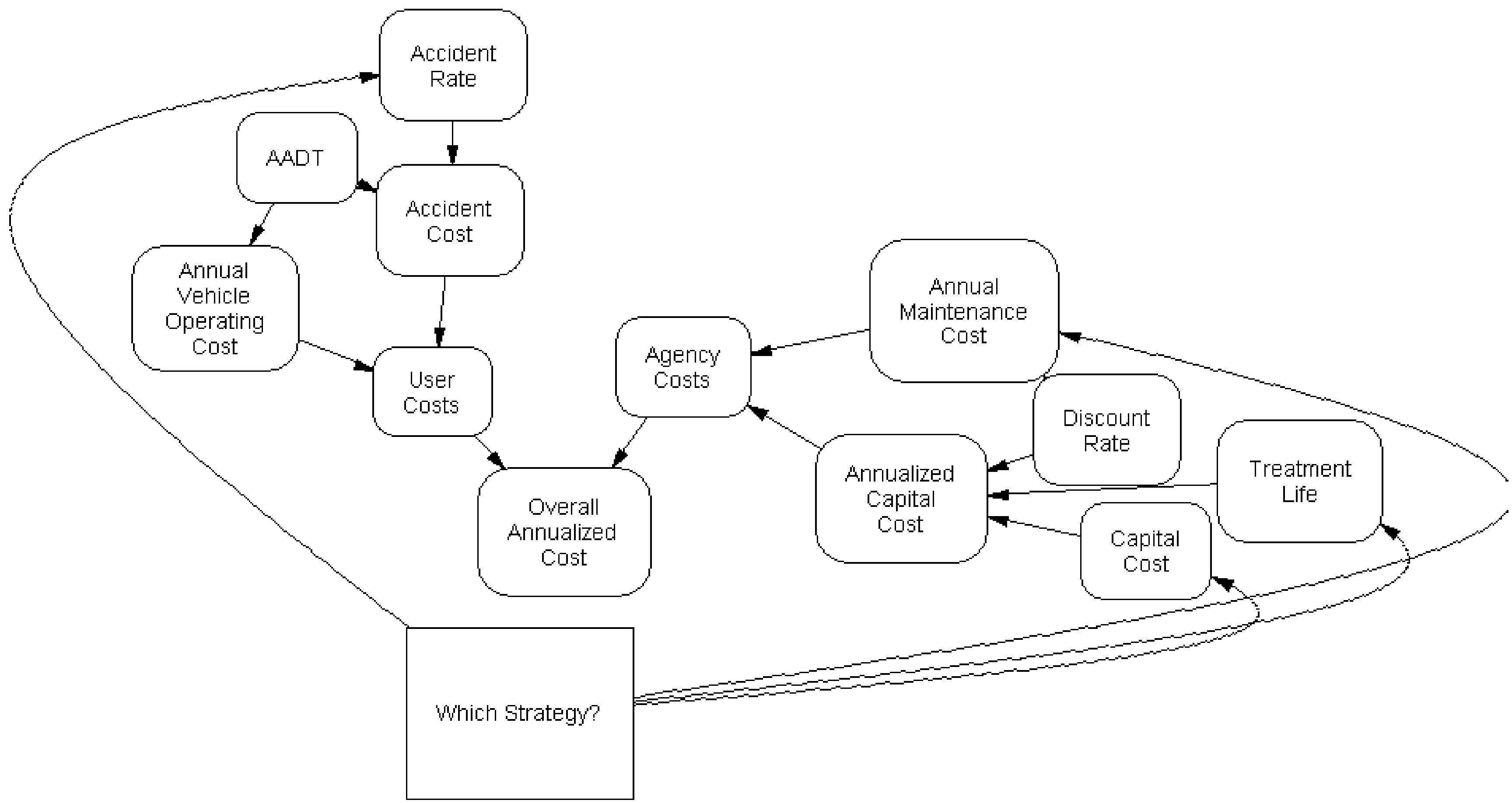


FIGURE 4.2- INFLUENCE DIAGRAM

4.2 AGENCY COSTS

Agency costs are the capital and maintenance costs incurred by the agency over the life-cycle of the highway project. The components of agency costs in the influence diagram in Figure 4.2 include capital cost, treatment or service life, discount rate, and annual maintenance cost.

The *capital cost* is the initial cost to construct the project. Typical construction costs include surveying, testing, engineering, drainage structures, oil, granular material, equipment, land acquisition, traffic accommodation and any other incidental costs. Construction costs are unique for each project and vary depending on numerous factors. A few of the factors that affect the individual cost include, among others, the following:

- Location of project;
- Quantities required;
- Terrain;
- Type of work;
- Contractors.

Each management strategy has a different capital cost while Status Quo has no capital cost. Once the capital costs are determined, the treatment life is estimated so that costs can be determined on an annual basis.

The *treatment or service life* is the number of years a strategy is expected to last. If a road is constructed or rehabilitated in year 0, the agency designs it to last for a certain period. Once the road has failed, according to SHT criteria (SHT 2001b), the road would be rehabilitated or reconstructed. Because each strategy has a different expected service life, an estimate is made for the service life of each strategy so the capital cost can be discounted to an annual cost and then compared. As discussed in Chapter 2, annual costs are important so that equal comparisons could be made. The *discount rate* is the rate used to value money over time. SHT recommends using a 4% real discount rate (SHT 1995).

The *maintenance cost* is defined as the cost of preserving and repairing a highway and keeping it in a condition for safe, convenient, and economical use (Wright 1996). The objective, from a management point of view, is to pick, for every pavement state, the specific maintenance action that is best in the sense of minimizing the overall system cost (Nesbitt et al. 1992). Extensive research has been done over the years by agencies to determine what their maintenance strategy should be to best maintain their assets. Maintenance can be divided into four general categories: preventative, repair, rehabilitation, and reconstruction (Nesbitt et al., 1992). The relationship of each maintenance strategy over time is illustrated in Figure 4.3.

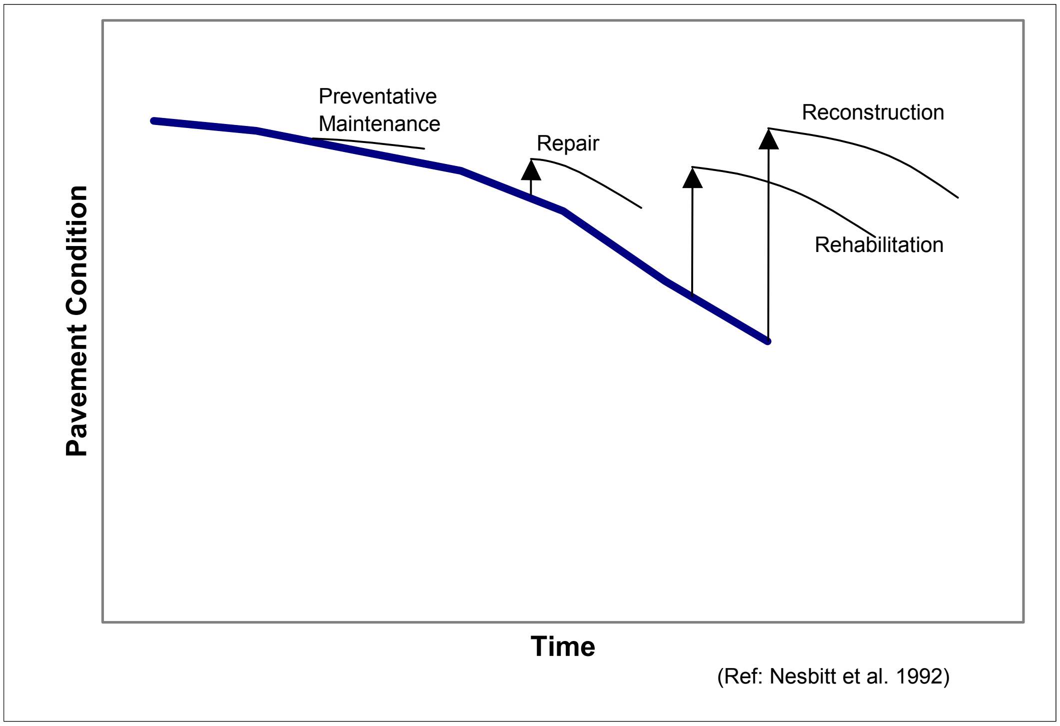


FIGURE 4.3 FOUR TYPES OF MAINTENANCE STRATEGIES

To determine the annual maintenance cost for the strategies, the year and cost for the maintenance is estimated, discounted to a present value, and then discounted to an annual cost. Maintenance costs differ for every strategy and can be different for each project.

4.3 USER COSTS

For this research, user costs included vehicle operating cost and the estimated accident cost. *Vehicle operating costs* (VOC) are the cost of operating a vehicle over a particular section of highway. Vehicle operating costs vary among vehicles and highway conditions; therefore, they were very hard to estimate and to justify in a deterministic sense. As well, models are a mathematical representation of real life so that care has to be taken when modeling vehicle operating costs to ensure that the results are reasonable and defensible. SHT uses a model developed by Sparks and Associates (1993), in conjunction with Berthelot (1992), for determining vehicle operating costs. Because this model has been accepted in Saskatchewan, it will be used to determine vehicle operating costs for the different management strategies on projects. The costs are summarized $/km/year.

The *accident rate* is the value used to express accident experiences. Accident data is expressed as average annual accident rate in accidents per million vehicle kilometres. SHT obtains accident data from the provincial Traffic Accident Information System (TAIS). The TAIS database is used to store accident information obtained from the Royal Canadian Mounted Police accident forms. Data collected from these accident reports include time, accident configuration, main contributing factors, number of vehicles, number of occupants, road conditions, as well as other details. To get a reliable estimate of the accident rate, researchers state that there must be at least 5 years of accident data (SHT 1995). Fatal, injury, and property damage are the three classifications of severity of accidents. Table 4.1 quantifies SHT accident costs for the purpose of economic analysis.

TABLE 4.1 ACCIDENT COSTS (SHT 1995)

Fatal	Personal Injury	Property Damage
$1,400,000	$180,000	$4,800

The default accident distribution for accident severity on a two-lane road is shown in Table 4.2.

TABLE 4.2 ACCIDENT SEVERITY DISTRIBUTION (SHT 1995)

Fatal	Personal Injury	Property Damage
2.72 %	31.05 %	66.23 %

The data from Table 4.3 is used to estimate the accident rate in the analysis for the proposed management strategies, except Status Quo. The calculated accident rate from historic data is used for estimating future accidents on existing highways. However, if the estimated rates for the strategies in Table 4.3 are higher than the existing accident rate, the existing accident rate is used for the strategies. This is done because the accident rates from Table 4.3 are an estimate for the province. If the accident rate is lower and the highway is upgraded, accident rates should not increase (SHT 1995). Once the accident rates and AADT are known, an annual $/km/year *accident cost* is calculated.

TABLE 4.3 DEFAULT ACCIDENT RATES FOR UPGRADE ROADWAYS (SHT 1995)

Roadway Type	Mean Accident Rate (accident/million vehicle km)	25^{th} Percentile (accident/million vehicle km)	75^{th} Percentile (accident/million vehicle km)
Paved, 2 Lane> 11.5m top width	0.414	0.3	0.59
Paved, 2 Lane, 9 to 11.5m top width	0.491	0.36	0.65
Paved, 2 Lane, 7 to 9m top width	0.617	0.4	0.87
Gravel	0.8	0.6	1.4

The *AADT* is the annual average daily traffic on the highway, split by percentage into passenger and commercial traffic. The AADT is used to predict vehicle operating and accident costs on a section of highway. As stated in the Scope in Chapter 1, the AADT is assumed to remain the same between strategies.

CHAPTER 5 ANALYSIS

5.1 INTRODUCTION

The purpose of the research, as outlined in Chapter 1, was to develop a project level analysis framework capable of determining the management strategy that minimizes life-cycle agency plus user costs while meeting or exceeding SHT road surface and road structural standards. To achieve this goal and demonstrate the model, a project on Highway No. 19 was evaluated.

5.2 APPLICATION OF FRAMEWORK

The project that was chosen was Highway No. 19, south of Highway No. 15, as illustrated in Figure 5.1. Highway No. 19 is a TMS highway that experienced a substantial increase in heavy truck traffic from the potato industry and is beginning to experience increased truck traffic associated with grain moving into the inland terminal at Loreburn that was built in 2000. Highway No. 19 also serves as a link to recreation sites, fishing, and sightseeing in the Gardiner Dam region. AADT volumes were estimated at 500 vehicles per day with 11% commercial traffic. SHT considers commercial traffic all vehicles except cars and light trucks.

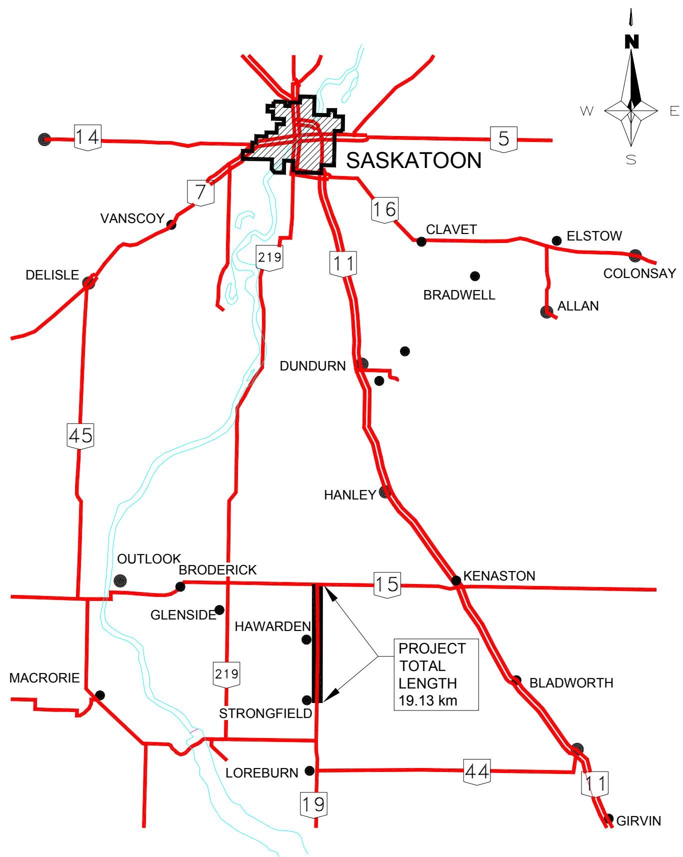


FIGURE 5.1 PROJECT

The first step of the process, as described in Chapter 4, was to determine the applicable SHT standard. Because the traffic volumes were 500 vehicles per day (SHT 2002), the SHT standard that applied was a structural, dust-free highway. The two strategies that met the design standard were Conventional and FDCS strategies. This eliminated the Gravel Reversion strategy. The Municipal Partnership strategy was excluded from the analysis because at a network level Highway No. 219 runs parallel Highway No. 19 and Highway No. 219 was weight restricted while Highway No. 19 was designated as the heavy route. Status Quo was also considered, even though it did not meet SHT standards, because Agencies may be forced to do nothing due to budget constraints.

Once the strategies were chosen, the next step was to determine the design of the Conventional and FDCS structures. The Conventional structure that was chosen was 300 mm of sub-base and 150 mm of base (SHT 2001b). The surfacing structure chosen was a granular seal.

To determine the FDCS structure that was structurally equivalent to the Conventional structure, the mean peak deflections were taken from the Falling Weight Deflectometer readings on a similar portion of Highway No. 19 where the conventional structure project was used. The Falling Weight Deflectometer uses a weight that is dropped on the surface of the road structure and measures the deflections of the road surface. The average mean peak deflection from the existing 300 mm sub-base and 150 mm base structure on Highway No. 19 was compared against the FDCS mean peak deflections to get a deflection comparison (Gerbrandt 2002). This was the method used to determine the equivalent FDCS structure to Conventional structure for this example because the Falling Weight Deflectometer data were available; however, if no data were available, material samples would have been obtained and analyzed in the lab to determine the FDCS structure that was structurally equivalent to the Conventional strategy. For this example, the FDCS structure that was determined to be equivalent to the Conventional structure, based on the results from the other Highway No. 19 project, was 300 mm of FDCS treated into the subgrade.

The highway geometrics for 500 vehicles per day is an U110-7010 (C/DS/SS), according to SHT standards (SHT 1991). U110-7010 (C/DS/SS) is a 110 km/hr design speed, 7.0 m top width and 1.0 m shoulders on each side. The structure is a pavement C, as described in Chapter 3, with a granular double seal on the driving lanes and a single seal on the shoulder. After the highway geometrics and design structures were established, the agency costs for the Conventional, FDCS, and Status Quo strategies were determined and are shown in Table 5.1. As shown in Table 5.1, the maintenance cost for Status Quo was $4,500/km/year. However, as the road continued to deteriorate, maintenance would no longer be practical.

TABLE 5.1 AGENCY COSTS AND INPUTS

Type of Agency Cost	Description	Units	Highway No. 19
Capital	**Conventional**		
	Sub-base Hauling Distance	km	15
	Base Hauling Distance	km	30
	Cost of Placing Sub-base	$/tonne	$3.00
	Cost of Placing Base	$/tonne	$3.50
	Cost of Crushing Base	$/tonne	$4.50
	Hauling Cost of Material	$/tkm	$0.15
	Cost for Regrading	$/m^3	$4.50
	Material Required for Regrading	m^3/km	10,800
	Full Depth Chemical Strengthening		
	Cost for Chemical	$/tonne	$170
	Amount of Chemical for Stabilization	tonne/km	290
	Cost of Incorporating into Subgrade	$/m^2	$1.65
	Both		
	Surfacing Cost (double seal)	$/m^2	$2.00
	Engineering, Sundries	total	$25,000
Maintenance	Conventional	$/km/yr	$2,915
	Full Depth Reclamation	$/km/yr	$2,915
	Status Quo	$/km/yr	$4,500 +

Once the agency costs were determined, user costs were calculated. To determine the VOC, the traffic distribution had to be determined. Based on data supplied by the SHT Traffic Engineer, the traffic was distributed according to Table 5.2. Berthelot's model (Berthelot 1992) was used to determine the VOC for four classes of vehicles on Highway No. 19, as shown in Table 5.3. The values were calculated by SHT, based on year 2000 data. The inputs for accident costs are shown in Table 4.3 and were used to calculate accident costs (SHT 1995).

TABLE 5.2 TRAFFIC DESCRIPTION AND DISTRIBUTION

Type	Description	Traffic Distribuiton
PCAR	Cars and Light Trucks	89%
AX3	Truck with 3 axles	4%
AX5	Tractor & Semi-Trailer 5 axles	3%
AX8	Tractor & Semi-Trailer 8 axles	4%

TABLE 5.3 VOC FOR PROJECT

Strategy	Type of Vehicle	Units	Low Value	Expected Value	High Value
Conventional and TerraCem	PCAR	$/km	$0.202	$0.241	$0.281
	AX3	$/km	$0.330	$0.391	$0.452
	AX5	$/km	$0.507	$0.582	$0.656
	AX8	$/km	$0.638	$0.732	$0.825
Status Quo	PCAR	$/km	$0.221	$0.275	$0.316
	AX3	$/km	$0.334	$0.418	$0.441
	AX5	$/km	$0.532	$0.614	$0.676
	AX8	$/km	$0.662	$0.773	$0.910

Once the individual Conventional, FDCS, and Status Quo inputs were identified, the total user and agency costs for each strategy were calculated using the model illustrated by the DPL influence diagram in Figure 4.2. The capital costs were discounted over their expected service life to estimate an annual cost. The results of the user and agency cost calculations are summarized in Figure 5.2.

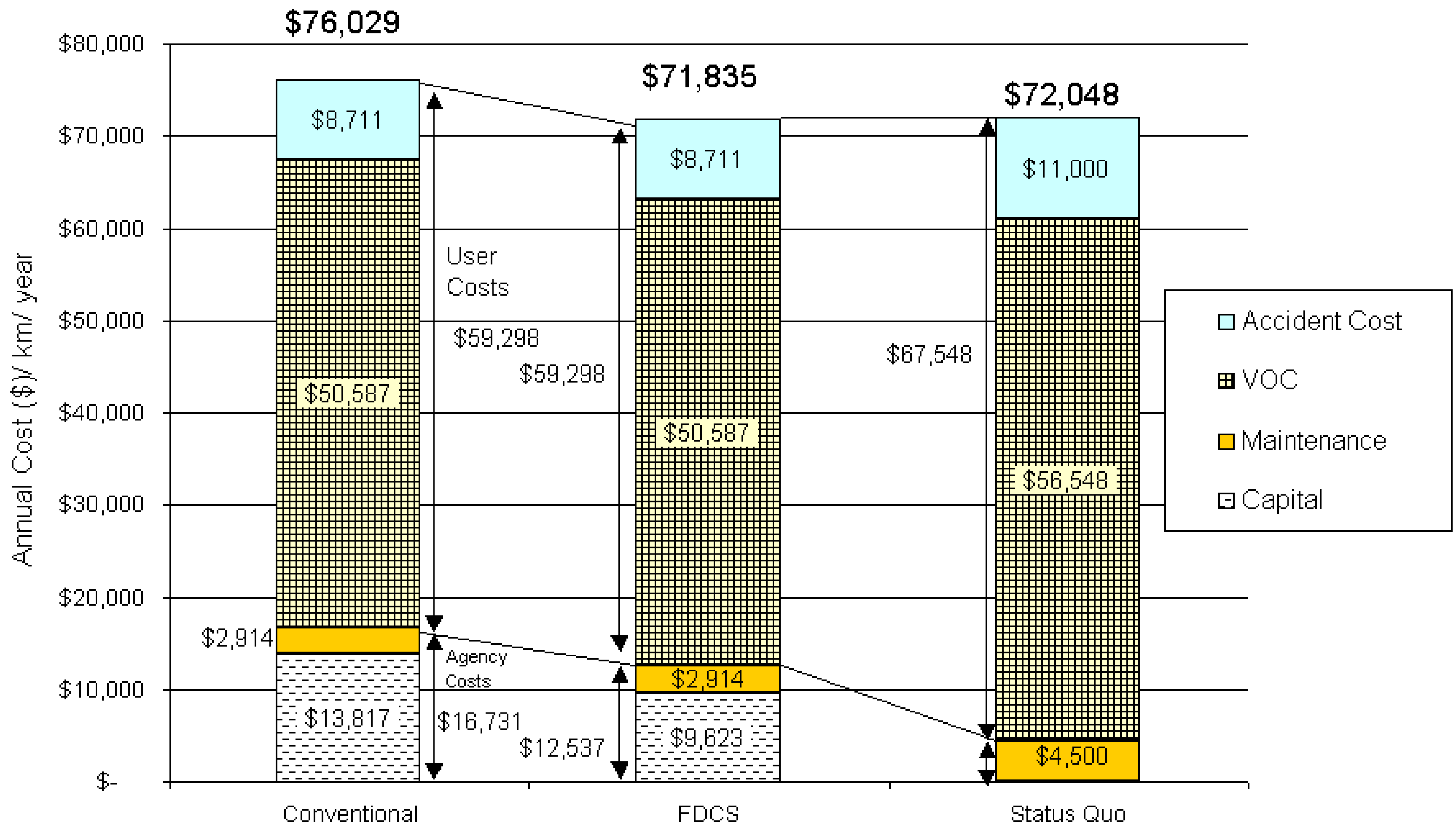


FIGURE 5.2 EQUIVALENT ANNUAL COST AGENCY AND USER COSTS

As shown in Figure 5.2, the FDCS strategy was approximately $4,500/km/year less expensive than the Conventional strategy when both strategies were assigned a 15 year service life. Also shown in Figure 5.2 is that the FDCS strategy had a lower total cost than Status Quo. This includes user costs, which are higher for Status Quo because of the condition of the TMS, but agencies may not consider them in their decision. In Figure 5.2, user costs for the Conventional and FDCS strategies were both $59,298/km annually. They were equivalent because the structures were equivalent, with respect to the Falling Weight Deflectometer, and the roadway width and surface were the same so VOC and Accident Costs for both strategies were equal. Maintenance costs were also assumed the same for the Conventional and FDCS strategies because long-term performance of the FDCS strategy, while uncertain, would be expected to be comparable to the Conventional strategy. This is substantiated from the performance of the test sections on Highway No. 19 over the past three years, it appeared that the maintenance costs were similar between the two strategies.

In this example, as shown in Figure 5.2, only the capital cost differed between the Conventional and FDCS strategies. The capital cost for the FDCS strategy was $103,900/km and $153,625/km for the Conventional strategy. Note that $48,600/km of the Conventional capital cost was required for widening the side slopes of the highway so that the required top width was maintained. The FDCS strategy did not require widening because the structure was strengthened using the "build down" technique instead of granular material being needed to strengthen upwards, thus requiring widening. Based on this deterministic analysis, including an assumption related to the service life of the FDCS being 15 years, the FDCS strategy was the lowest cost strategy for this project. However, a sensitivity and probabilistic analysis was also completed.

5.3 SENSITIVITY ANALYSIS

The next step in the modeling process was to complete a sensitivity analysis. However, for this example the maintenance and user costs were equivalent for both strategies so they were excluded from the sensitivity analysis. Although the agency costs for this project were known values (Table 5.1), a sensitivity analysis was completed because of the interest in which inputs were the most sensitive. For the purpose of understanding which variables were the most sensitive, Table 5.4 has high and low values that may be encountered in Saskatchewan.

TABLE 5.4 POSSIBLE HIGH AND LOW VALUES

Type of Agency Cost	Description	Units	Low Value	Expected Value	High Value
Capital	**Conventional**				
	Sub-base Hauling Distance	km	5	15	20
	Base Hauling Distance	km	10	30	75
	Cost of Placing Sub-base	$/tonne	$2.00	$3.00	$4.00
	Cost of Placing Base	$/tonne	$2.50	$3.50	$4.50
	Cost of Crushing Base	$/tonne	$3.00	$4.50	$5.00
	Hauling Cost of Material	$/tkm	$0.13	$0.15	$0.17
	Cost for Regrading	$/m^3	$3.00	$4.50	$5.50
	Material Required for Regrading	m^3/km	-	10,800	20,000
	Full Depth Chemical Strengthening				
	Cost for Chemical	$/tonne	$150	$170	$200
	Amount of Chemical for Stabilization	tonne/km	200	290	320
	Cost of Incorporating into Subgrade	$/m^2	$1.20	$1.65	$2.00
	Thickness of Base Required	mm	0	0	150
	Both				
	Surfacing Cost (double seal)	$/m^2	$1.80	$2.00	$2.20
	Engineering, Sundries	total	$20,000	$25,000	$30,000

An expected value tornado diagram was constructed for the conventional and FDCS strategies, as shown in Figure 5.3. As illustrated in Figure 5.3, the amount of material required for widening the highway and the base haul distance had the most impact on the cost of the conventional strategy. From Figure 5.3, if no material was required for widening with the Conventional method, the cost was \$105,024/km; however, if the highway required 20,000m^3/km, the cost was \$195,024/km. For the FDCS, the most sensitive variable to the capital cost was when base was required. As well, Figure 5.3 illustrates the relative sensitivity between the two strategies.

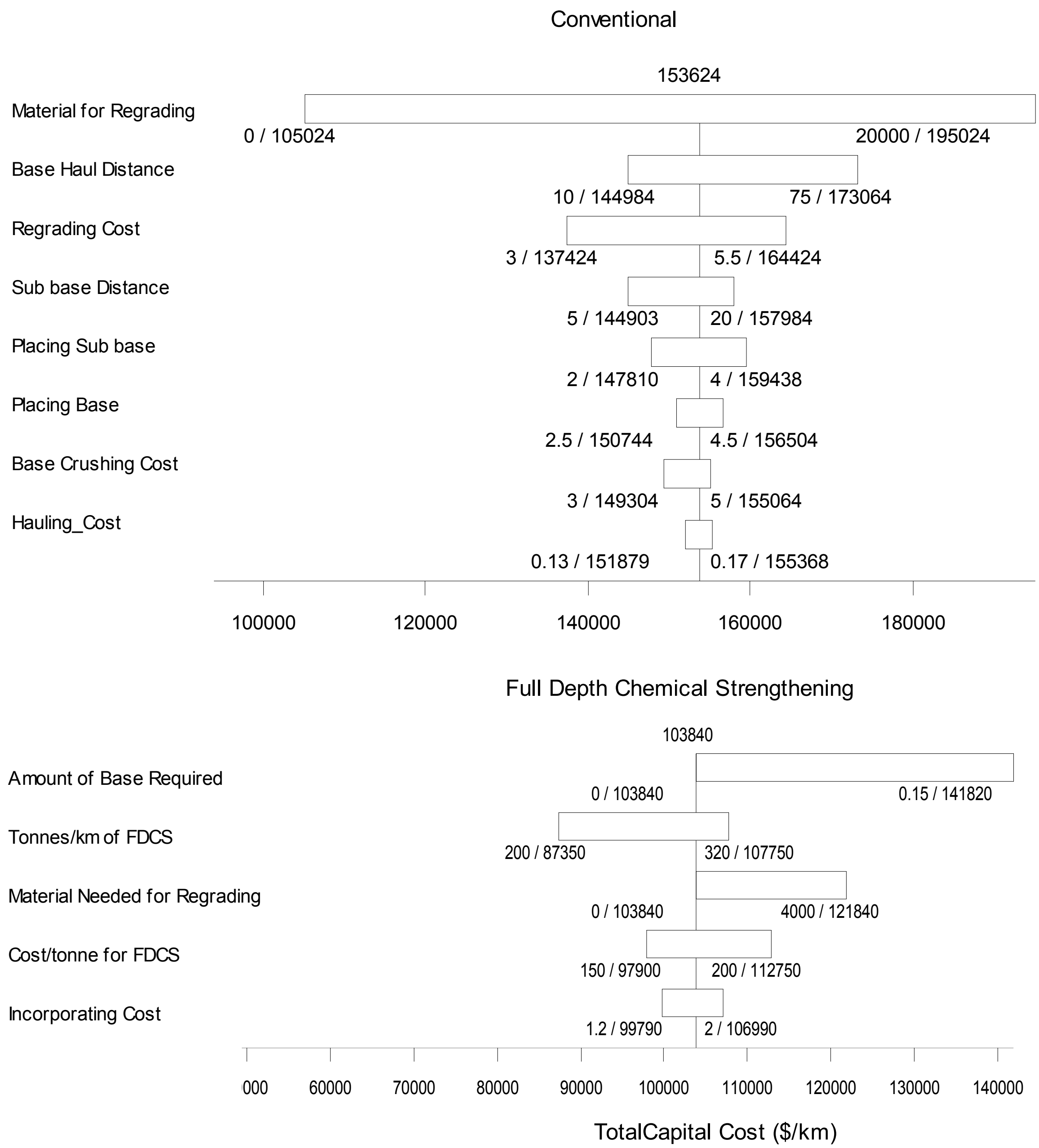


FIGURE 5.3 SENSITIVITY ANALYSIS

A sensitivity analysis on the expected service life for the strategies was completed. For both strategies, the low and high values of expected service life were 5 and 20 years, respectively. Based on the results from the analysis, the life of the strategies affected the lowest cost strategy; therefore, probabilistic modeling of expected service life was completed. If there were other uncertainties, they could have also been modeled.

5.4 PROBABILISTIC MODELING

The focus of the probabilistic modeling was to evaluate the effect of uncertainty in expected service life upon the cost of the Conventional and FDCS strategies. User and maintenance costs were not included in the probabilistic modeling because, in this example, they were the same for the two strategies. Only the capital costs between the two strategies were different and therefore modeled.

For the previous deterministic analysis, the expected service life of the Conventional and Alternative strategies was 15 years. However, because of the uncertainty with expected service life, the capital costs for the two strategies were shown as annual values over a range of expected service lives, as shown in Figure 5.4. As illustrated in Figure 5.4, if the Conventional treatment lasts 15 years, the FDCS has to last approximately ten years to provide equivalent annual costs.

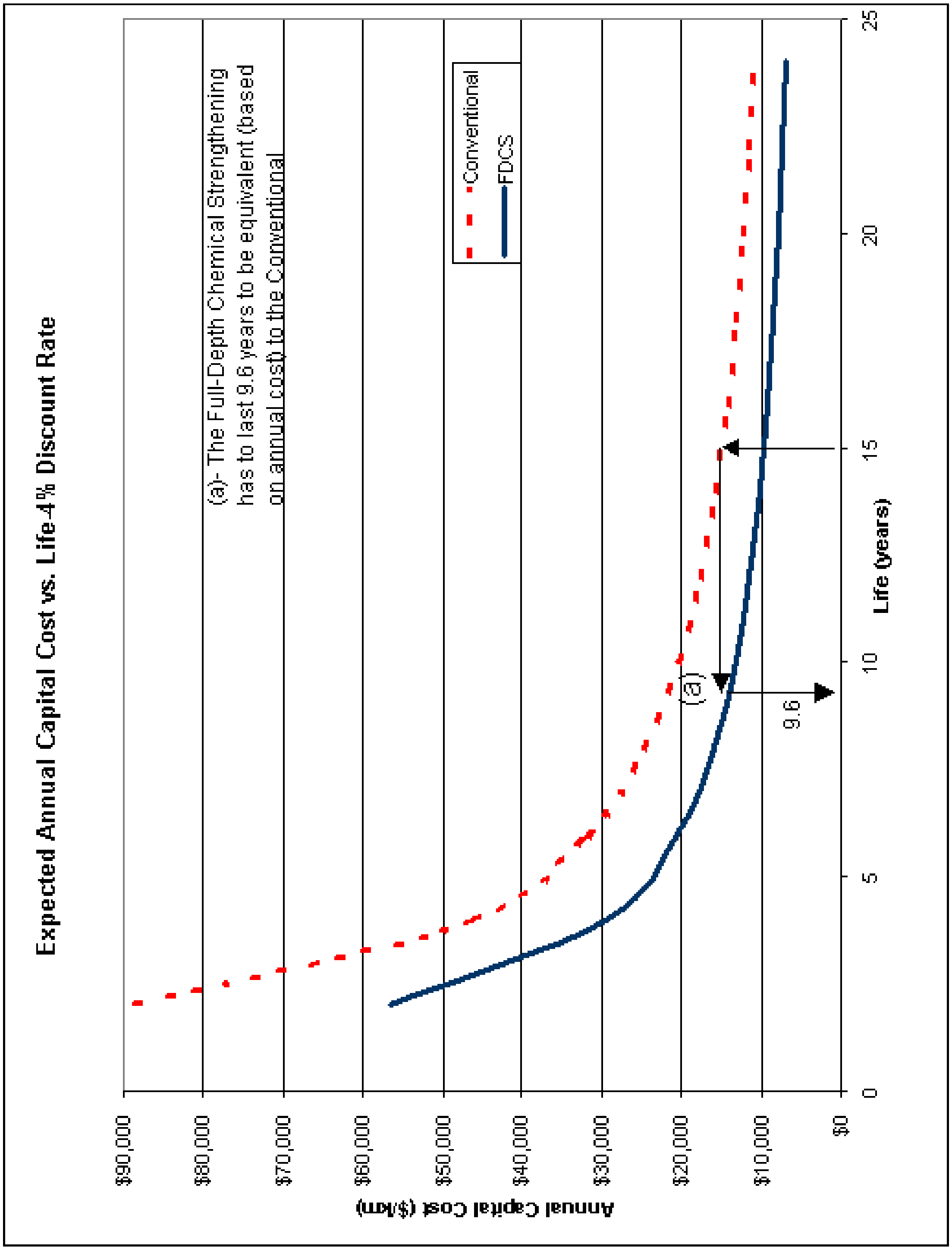
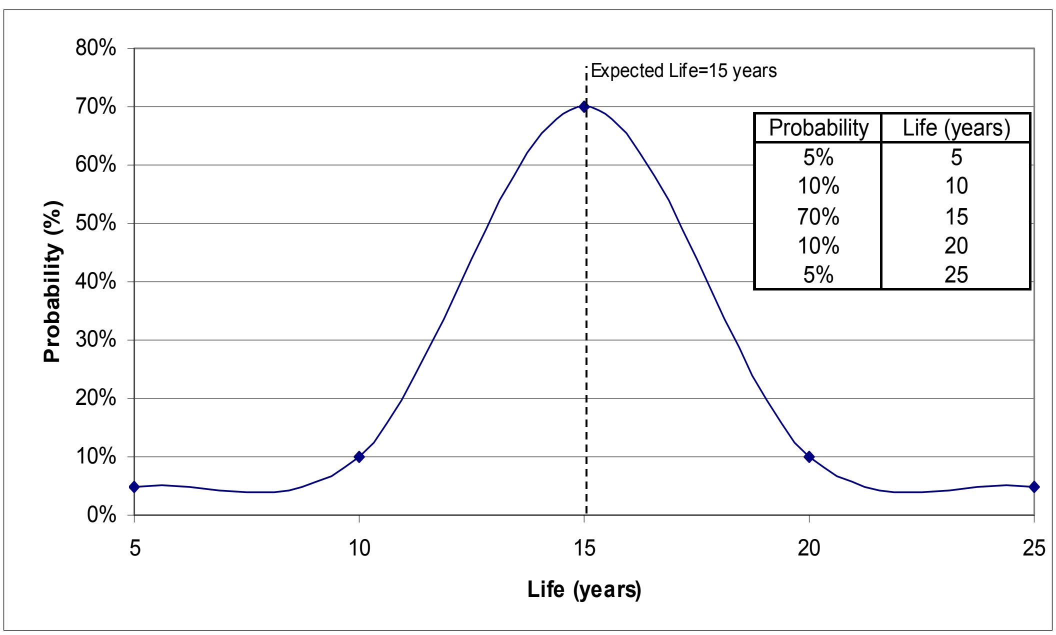


FIGURE 5.4 EXPECTED ANNUAL COST VERSUS LIFE

Because of the lack of long-term performance results in Saskatchewan with FDCS treated subgrades, SHT wanted to evaluate how different expected service lives for the

FDCS strategy affected annual costs compared to the relatively predictable Conventional strategy.

SHT has records of the performance of Conventional strategies back to 1952 (SHT 2001c). For example, since 1952 there were over 1500 records of structures equivalent to the Highway No. 19 project (SHT 2001c) across the province. Once the projects were identified that had similar traffic, a determination was made on their service life by establishing when they had to be rehabilitated. This was not exact because weather conditions and traffic could have affected the performance and strengthening may not have occurred after failure. Based on these performance records for structures in similar soils with similar traffic and in questioning SHT Maintenance personnel on the expected performance, the probability distribution of expected service life for the Conventional treatments for this project is shown in Figure 5.5.

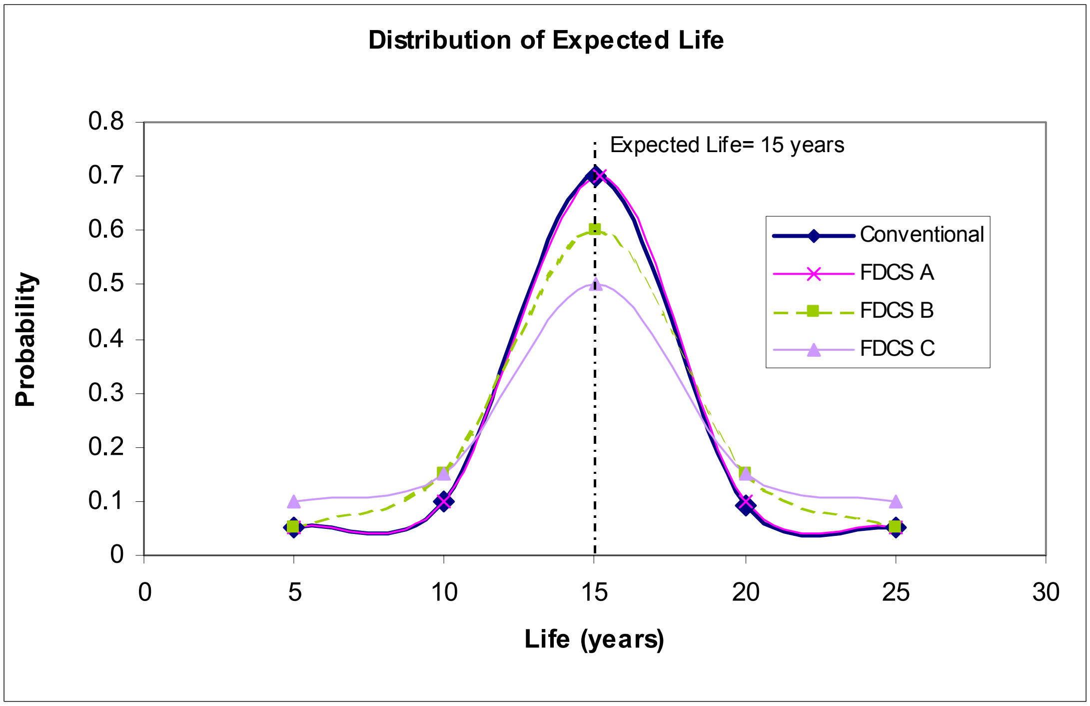


Probability	Life (years)
5%	5
10%	10
70%	15
10%	20
5%	25

FIGURE 5.5 PROBABILITY DISTRIBUTION FOR CONVENTIONAL SERVICE LIFE

By providing different probability distributions for the service life of the FDCS strategy, it was possible to show how costs changed over different expected service life distributions compared against the Conventional strategy. Seven probability distributions, using a stochastic process, across an expected service life of 10, 15, and 20 years were analyzed for the FDCS strategy in order to illustrate the effect uncertainty in service life has upon expected annual costs.

As shown in Figure 5.6, the FDCS service life distribution A, B, and C have the same expected service life as the Conventional strategy (i.e. 15 years) except that the distributions for FDCS have been “flattened and broadened” to quantify the effect increasing uncertainty (represented by the flatten-broaden distributions) has on the estimates of annual costs.



Legend					
	Probability Distribution				
	5 years	10 years	15 years	20 years	25 years
Conventional	5%	10%	70%	10%	5%
FDCS A	5%	10%	70%	10%	5%
FDCS B	5%	15%	60%	15%	5%
FDCS C	10%	15%	50%	15%	10%

FIGURE 5.6 DISTRIBUTION OF EXPECTED SERVICE LIFE = 15 YEARS

The expected annual cost for the three FDCS distributions, taken from Figure 5.6, are shown in Figure 5.7. As shown in Figure 5.7, all three FDCS distributions have a lower expected annual cost than the Conventional strategy. Figure 5.8 shows a cumulative probability distribution from the data from Figure 5.7. As illustrated in Figure 5.8, the FDCS strategies have a lower expected cost throughout most of the distribution. The separation between the strategies signifies the higher confidence that the FDCS strategy will be less expensive. The more separation in the distributions the larger difference in expected cost. For example, the probability that the expected cost of the Conventional strategy is less than $12,500/km is 60%. At 60% for the FDCS strategy, the expected cost is less than $9,000/km.

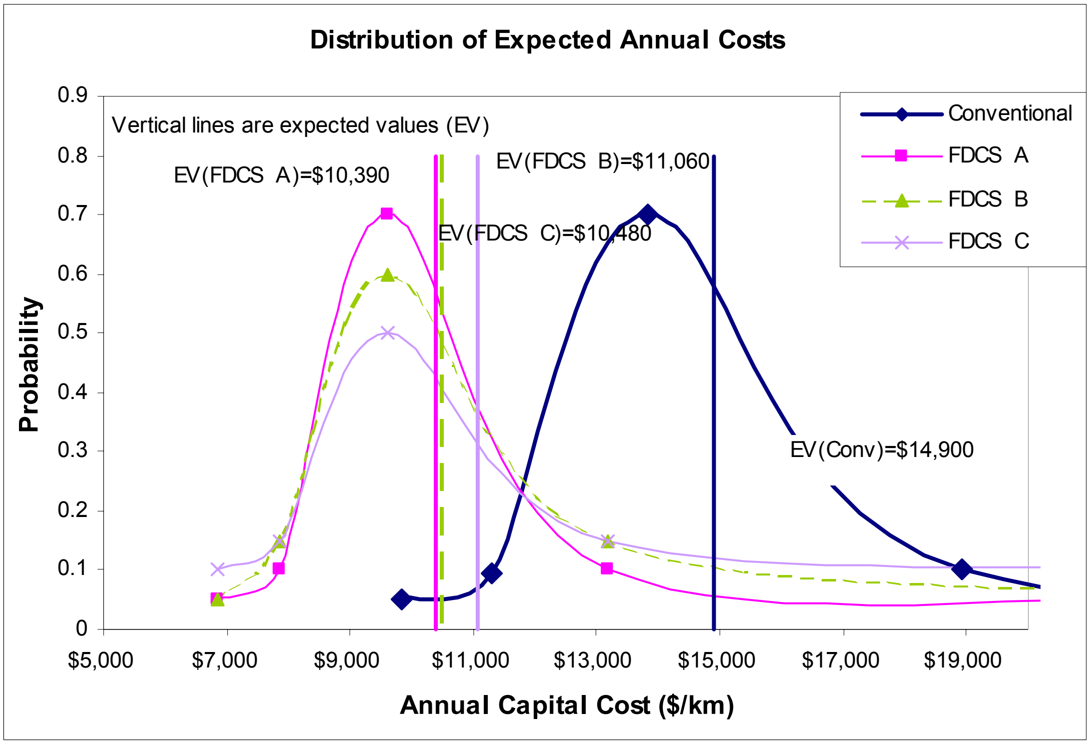


FIGURE 5.7 DISTRIBUTION OF EXPECTED ANNUAL COST FOR EXPECTED SERVICE LIFE = 15 YEARS

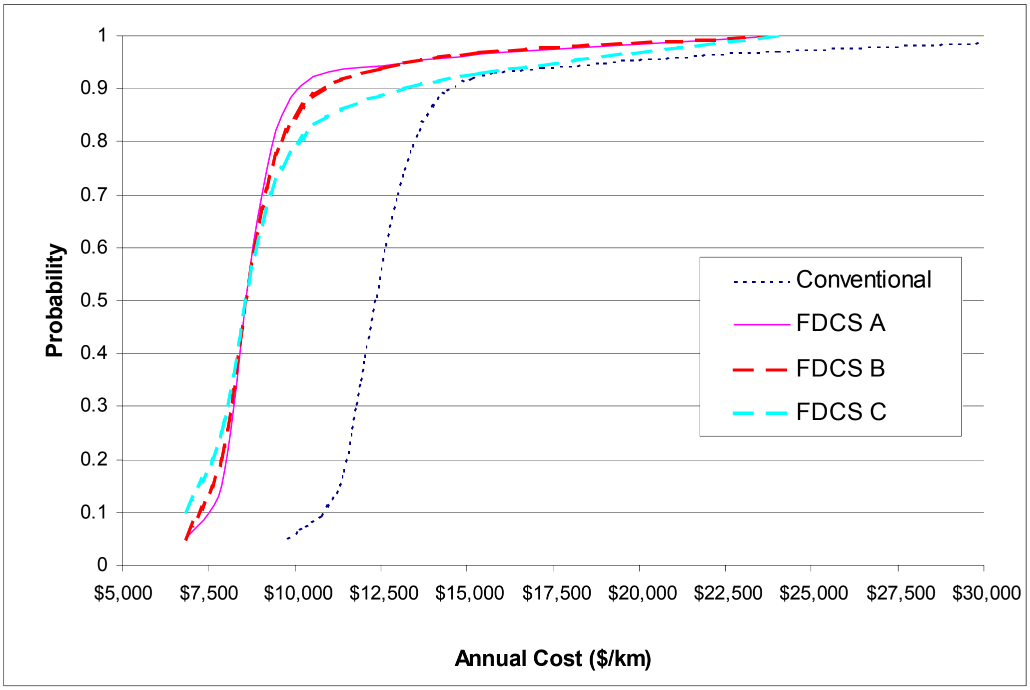
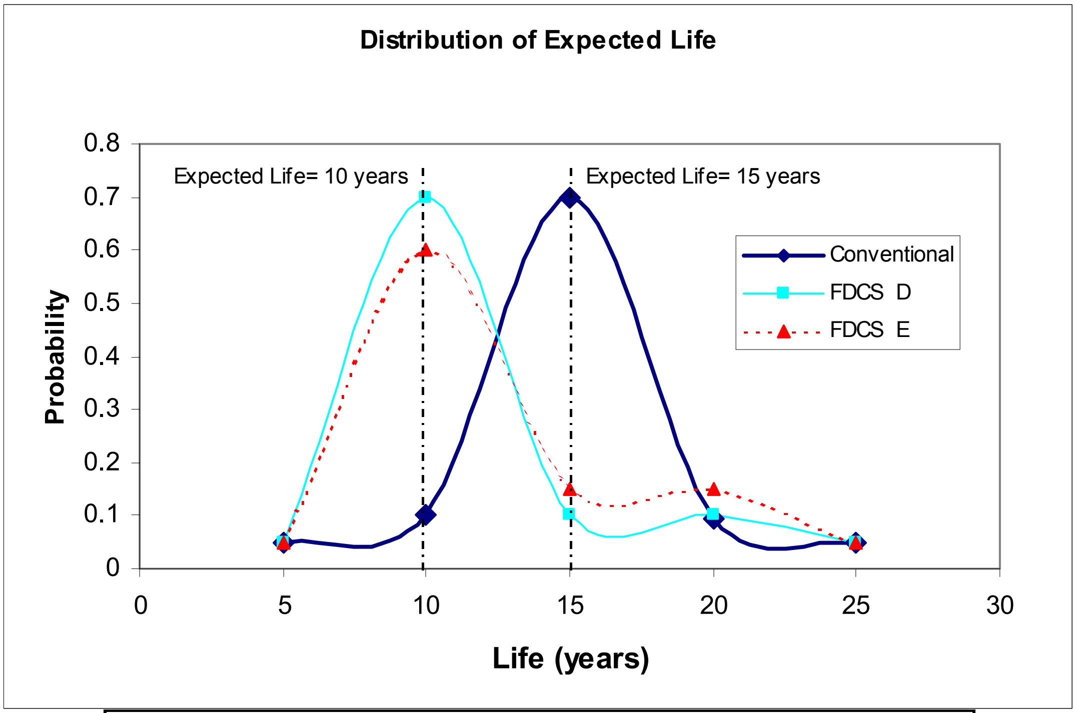


FIGURE 5.8 CUMULATIVE PROBABILITY DISTRIBUTION EXPECTED SERVICE LIFE FOR FDCS = 15 YEARS

In Figure 5.9, the expected service life distribution for FDCS was lowered to 10 years and compared with the 15 year expected service life for the Conventional strategy by flattening and widening the 10 year expected service life distribution. Figure 5.10 illustrates the estimated annual cost distributions for the FDCS strategies, derived from Figure 5.9. As shown in Figure 5.10, the decrease in expected service life from 15 years to 10 years for the FDCS strategies increased the expected annual cost, resulting in a narrower margin between the expected value for the FDCS and Conventional strategies. Figure 5.11 illustrates the cumulative probability distribution from Figure 5.10. As shown in Figure 5.11, although the FDCS strategy has a lower expected cost than the Conventional strategy, the distributions are close together, which makes the decision more difficult for the agency.



Legend					
	Probability Distribution				
	5 years	10 years	15 years	20 years	25 years
Conventional	5%	10%	70%	10%	5%
FDCS D	5%	70%	10%	10%	5%
FDCS E	5%	60%	15%	15%	5%

FIGURE 5.9 DISTRIBUTION OF EXPECTED SERVICE LIFE = 10 YEARS

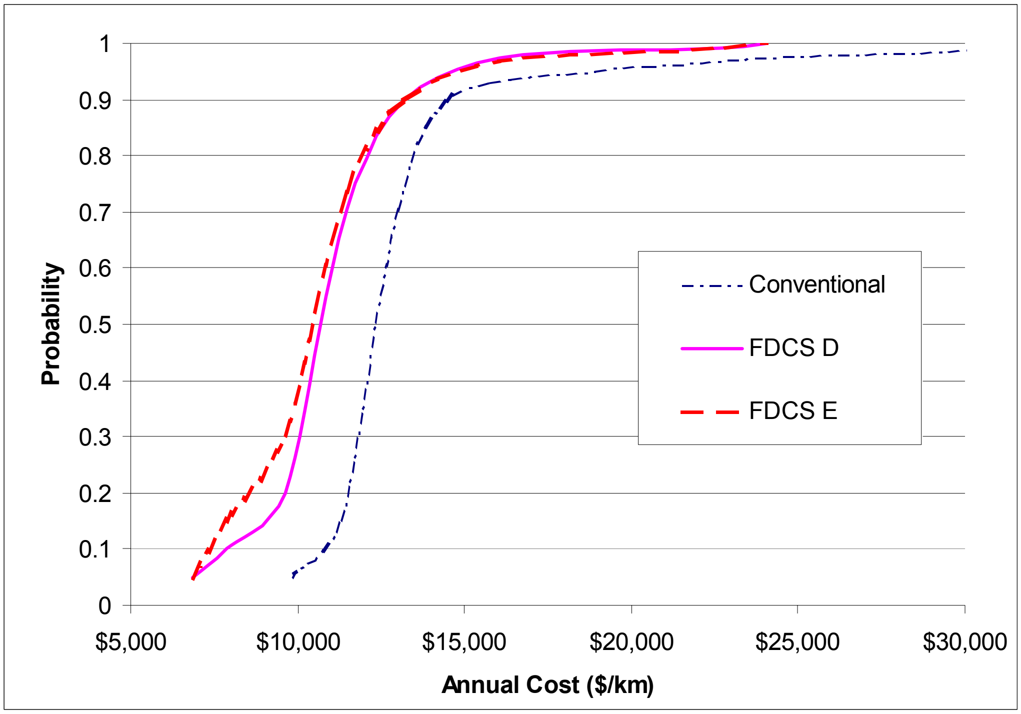


FIGURE 5.10 DISTRIBUTION OF EXPECTED ANNUAL COST FOR EXPECTED SERVICE LIFE = 10 YEARS

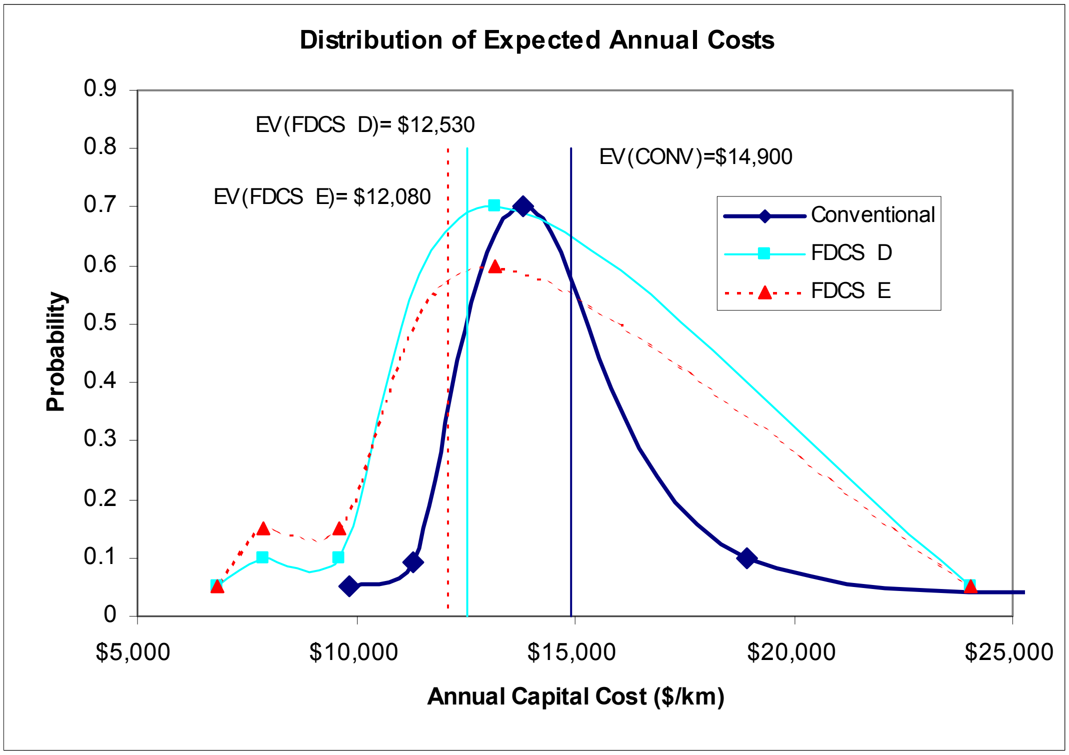
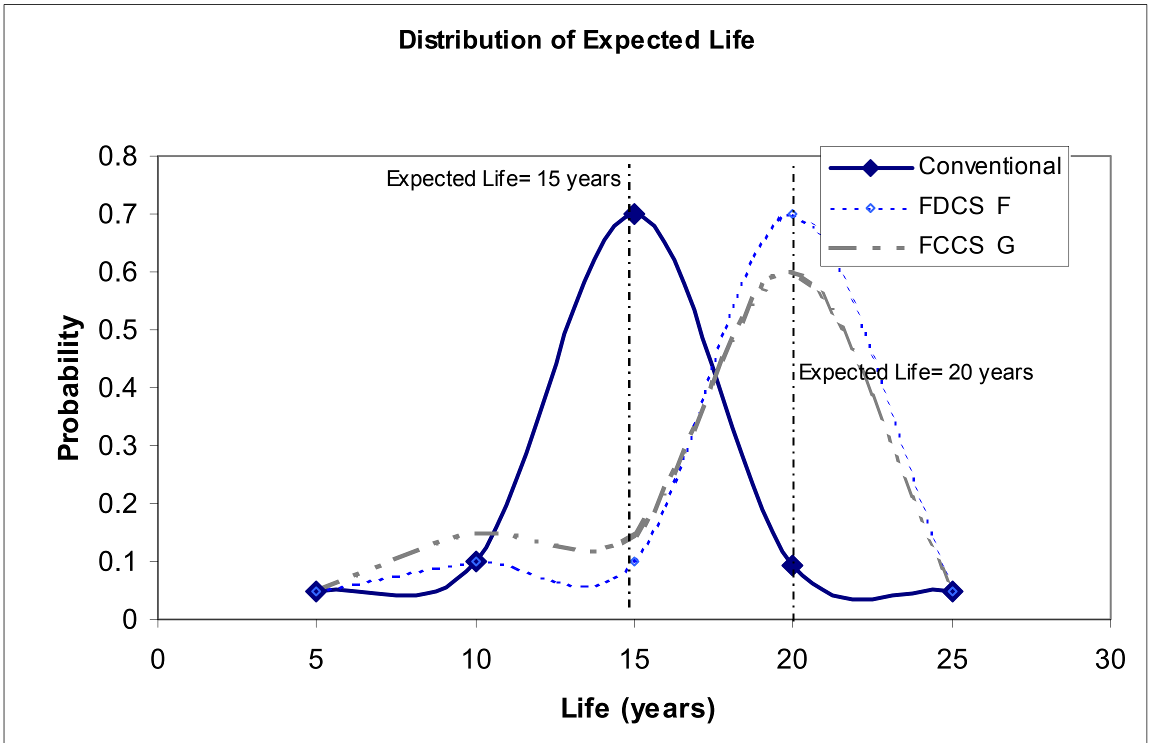


FIGURE 5.11 CUMULATIVE PROBABILITY DISTRIBUTION EXPECTED SERVICE LIFE FOR FDCS = 10 YEARS

The last FDCS probability distributions, as shown in Figure 5.12, were modeled with an expected service life of 20 years for the FDCS strategy, compared with the 15 year service life for the Conventional strategy. As shown in Figure 5.13, if the expected service life for the FDCS strategy was 20 years, the expected annual cost would be approximately $5,000/km/year lower for the FDCS strategy. Figure 5.14 illustrates the cumulative probability distribution for the FDCS 20 year expected service life. As shown in Figure 5.14, the FDCS strategy is to the left of the Conventional strategy and there is a relatively large difference between strategy distributions (compared with the 10 and 15 year expected service life for the FDCS strategy) so if the FDCS strategy lasts for 20 years, it would clearly be the lowest cost strategy.



Legend					
	Probability Distribution				
	5 years	10 years	15 years	20 years	25 years
Conventional	5%	10%	70%	10%	5%
FDCS F	5%	10%	10%	70%	5%
FDCS G	5%	15%	15%	60%	5%

FIGURE 5.12 DISTRIBUTION OF EXPECTED SERVICE LIFE = 20 YEARS

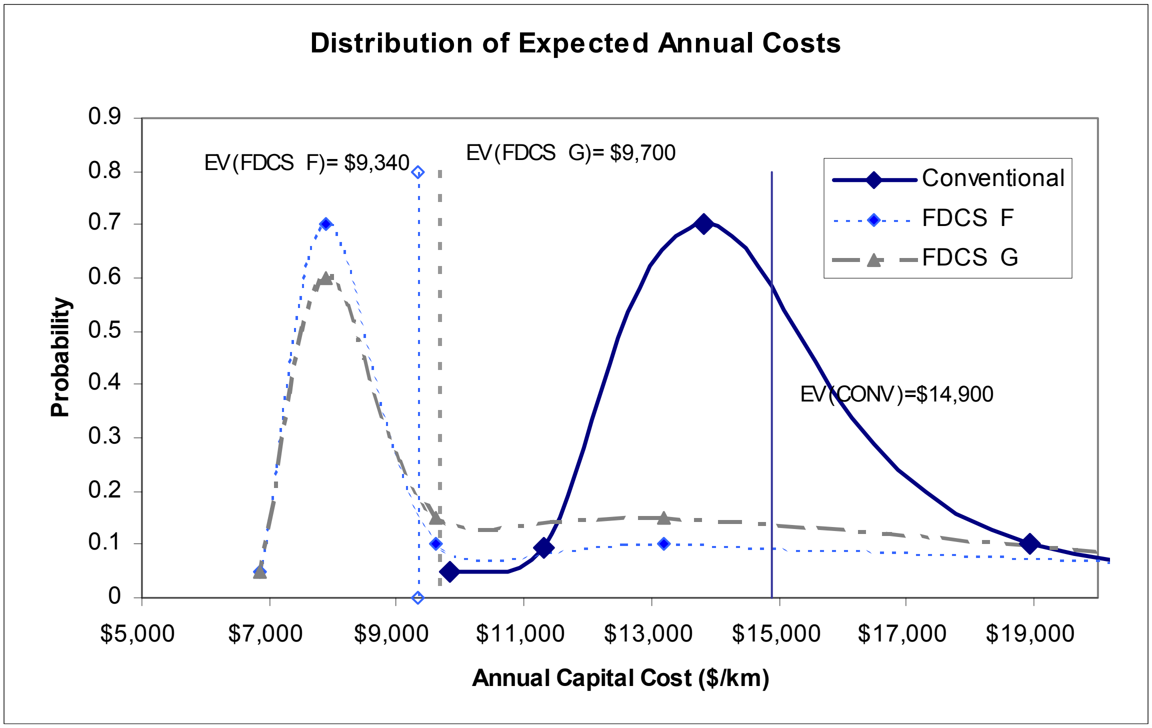


FIGURE 5.13 DISTRIBUTION OF EXPECTED ANNUAL COST FOR EXPECTED SERVICE LIFE = 20 YEARS

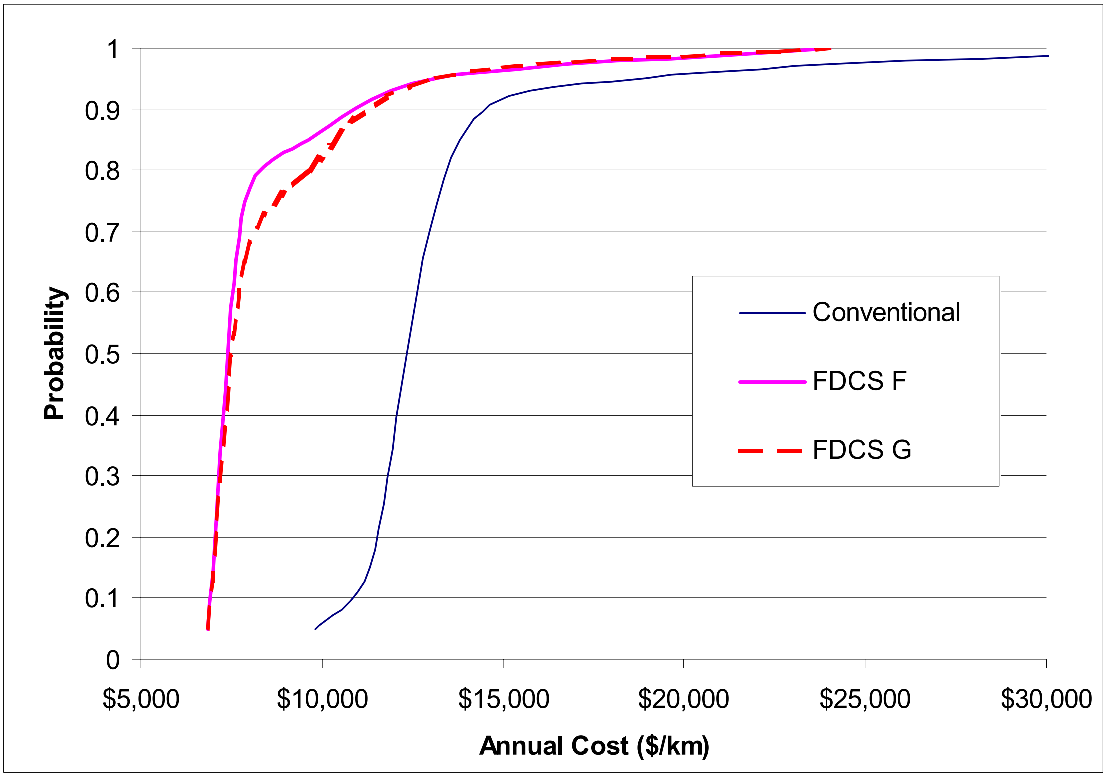


FIGURE 5.14 CUMULATIVE PROBABILITY DISTRIBUTION EXPECTED SERVICE LIFE FOR FDCS = 20 YEARS

5.5 ADVANCES IN TECHNOLOGY

Because the technology for FDCS is new in the province of Saskatchewan, costs are probably higher than expected and should decrease as the technology expands and production increases. For example, there are only three Contractors with rotomixers in the province. It is difficult to speculate on which costs would get less expensive but one should recognize this possibility. For example, rotomixing should get less expensive because of increased competition among Contractors and higher production rates. For the example on Highway No. 19, if the cost to incorporate was $0.25/m^2 instead of $1.65/m^2, the capital cost of the FDCS would be lowered by approximately $13,000/km.

As mentioned in Chapter 1, quality aggregate sources will continue to decrease, as the non-renewable resource is used. This will increase the project cost, as other aggregate sources will be required, resulting in longer hauls. For example, rock could be blasted from the Canadian Shield and hauled to the project. Because of the high dependency on quality aggregate for the conventional method, one can presume that the conventional cost to strengthen highways will increase in cost as aggregate sources diminish. This predicted trend has been depicted in Figure 5.15. From Figure 5.15, C1 is the difference in capital costs today. For the project on Highway No. 19, the difference between the conventional and FDCS was approximately $50,000/km.

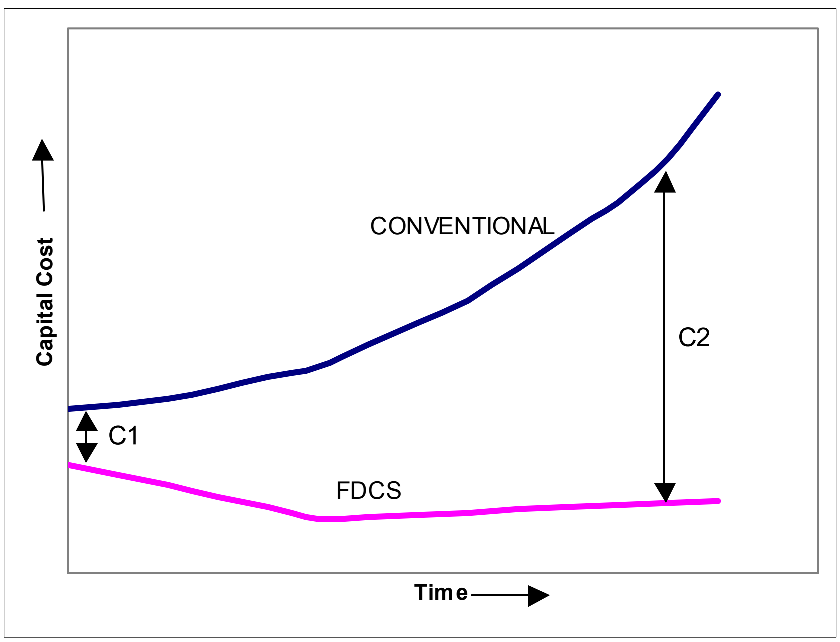


FIGURE 5.15 PREDICTED TREND WITH TECHNOLOGY

From Figure 5.15, C1 may be negative to $50,000/km or even higher on projects today but FDCS should decrease in cost over time as the province "catches up" with the technology then it should slightly with inflation cost of production increases. Looking into the future 15 to 20 years, C2 should be much greater than C1; however, the magnitude is unknown. Future cost savings to SHT could be millions of dollars annually.

CHAPTER 6 RESEARCH SUMMARY AND CONCLUSIONS

6.1 RESEARCH SUMMARY

The purpose of the research was to develop a project level analysis framework capable of determining the management strategy that minimizes life-cycle agency plus user costs while meeting or exceeding SHT road surface and road structural standards. With the deterioration of the TMS highway system in the past few years attributed to increasing heavy truck traffic, limited funds for the TMS highway system, and the high cost to conventionally strengthen TMS highways, SHT has been evaluating new strategies to manage the TMS highway system in an effort to reduce costs and meet or exceed SHT standards. To meet this standard, new alternative strategies like the cementitious blend of FDCS treated subgrades are being evaluated as a cost-effective solution; however, their long-term serviceability is uncertain at this time. As well, municipal partnerships are being evaluated as a cost-effective way to preserve TMS highways. By being able to minimize the total cost on projects, whether new or old strategies are chosen, SHT is able to assure the delivery of a cost-effective program.

A rational procedure was needed to evaluate the new and old strategies, in analytical terms, and to determine the total cost (user and road agency) to help to ensure that the chosen strategy is the lowest cost strategy that meets or exceeds SHT standards. To achieve the objective of this research, a framework including probabilistic models was developed that determines the total user and road agency costs for a strategy. Because of the uncertainty in predicting long-term service life of these new strategies like FDCS treated subgrades, probabilistic modeling was incorporated so the effect of uncertainty could be modeled.

6.2 CONCLUSIONS

To apply and demonstrate the model, a project on Highway No. 19 was provided. Because the FDCS and Conventional structures that were chosen were structurally equivalent, based on the Falling Weight Deflectometer data, only the capital costs were different. It was shown that the higher capital cost of the Conventional strategy was largely attributed to the widening that was required because of the additional height of the grade associated with the Conventional method. The deterministic analysis assumed a 15 year service life for both strategies. However, because the long-term performance of FDCS treated subgrades was uncertain, there was a need to explicitly model this uncertainty and explicitly quantify the effect that uncertainty in the service life of the FDCS treatment had upon the estimates of annual costs.

When the capital costs were annualized, the FDCS strategy had to last 10 years if the Conventional strategy lasts 15 years. Probabilistic modeling was completed on the uncertain service life for the FDCS strategy. When uncertainty in the service life of the FDCS strategy was considered, it was somewhat riskier than the Conventional method if it lasted 10 years relative to the Conventional at 15 years but a clear winner if its expected service life equalled or exceeded the 15 years of the Conventional strategy.

Because FDCS is new to Saskatchewan, capital costs should decrease as the technology expands and production increases. In contrast, as aggregate sources continue to be depleted in Saskatchewan, the capital cost of conventional strategies should increase at increasing rates. SHT must continue to expand the FDCS strategy because the difference in cost between conventional and FDCS will continue to increase over time, which could result in millions of dollars.

6.2 FUTURE WORK

In Chapter 1 of this research, the transportation cost to users by having secondary GVW limits instead of primary GVW limits on highways was mentioned but excluded from this research because of the difficulty in estimating these costs. If a relationship and model could be developed to measure the transportation cost savings and agency costs between the two weight limits, it could have a substantial impact on the priority and importance of projects. As well, a model could quantify the importance of this issue and provide concrete data to help decision makers in the overall selection of choosing the project that provides the lowest total cost to the users and agency.

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